Washington State Department of Ecology

Stormwater Treatment of Tire Contaminants Best Management Practices Effectiveness

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STORMWATER TREATMENT OF TIRE CONTAMINANTS BEST MANAGEMENT PRACTICES (BMP) EFFECTIVENESS

FINAL REPORT

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PROJECT BACKGROUND AND ACKNOWLEDGEMENTS

In the fall of 2021, the Washington State Department of Ecology (Ecology) released a request for qualifications and selected a Consultant Team with staff from Osborn Consulting, Inc., Evergreen StormH2O, Tetra Tech, and GeoEngineers to complete this work. The consultant team was advised and supported by a project advisory committee made up of researchers and staff from Ecology, the Washington State Department of Transportation (WSDOT), Washington State University (WSU), the University of Washington (UW), and the Technical Assessment Protocol - Ecology (TAPE) Program, who recommended literature to review, provided research updates, and comments on the draft versions of the report that were incorporated into this document.

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Chapter 1: Project Overview and Summary of Findings

Project Purpose

The antioxidant 6PPD and its byproduct 6PPD-quinone (6PPD-q) are chemicals recently discovered to come from tires and enter waterways through roadway runoff (stormwater). 6PPD-q has been linked to high mortality rates in coho salmon on the west coast of the United States. The goal of this project was to synthesize current knowledge of 6PPD and 6PPD-q, including physicochemical properties, sources, and fate and transport within the built environment, to assess which stormwater best management practices (BMPs) are expected to reduce concentrations of 6PPD and 6PPD-q in stormwater runoff. The objectives completed to achieve this goal included:

- Identify and review literature related to physicochemical properties, sources, fate and transport, and potential effective treatments of 6PPD and 6PPD-q (Chapters 2 and 3).
- Develop a basis from the literature for how to evaluate BMPs for their ability to capture, contain, and treat bound and dissolved 6PPD and 6PPD-q (Chapter 4).
- Apply the basis for how to evaluate BMPs to existing BMPs in the Washington Stormwater Management Manuals and stormwater design manuals from other states (Chapter 4).
- Summarize and prioritize research needs (Chapter 5) regarding physicochemical properties, sources, fate and transport, and potential effective BMPs for treating 6PPD and 6PPD-q.

Summary of Findings

The following paragraphs provide a summary of the findings organized by chapter followed by a summary of recommendations for future research.

<u>Chapter 2. Key Physicochemical Properties</u>

Summary and Synthesis of Current Knowledge - Of the sources reviewed and synthesized, 14 sources reported physicochemical properties for 6PPD and 6PPD-q. Half of the 14 sources reported modeled properties or a combination of model and lab or field data (e.g., CompTox Chemicals Dashboard, National Center for Biotechnology Information PubChem website). Fewer sources reported properties of 6PPD-q (5 of 14 sources) than 6PPD.

Findings Summary - The following properties and findings were identified through the review of sources.

- Both 6PPD and 6PPD-q appear to have an affinity for soil and organic matter, based on their relatively high log K_{ow} and log K_{oc}.
- The density and solubility of 6PPD suggest that it is likely to remain undissolved and will float, assuming it is not attached to another particle.
- 6PPD-q is more likely to travel in the dissolved phase than 6PPD. No density information was available for 6PPD-q.
- The degradation of 6PPD appears to vary in different environmental media with sources reporting short half-lives of a few hours in biologically active water, and longer half-lives of nearly a year in sediment (soils in water). The degradation of 6PPD-q also varies significantly (from just over a day in water to nearly a year in sediment) in different environmental media.

Knowledge Gaps - Because model data are based on assumed inputs and are generally used only as screening tools, we consider the limited amount of lab or field data on the following to be research gaps to test and understand:

- The affinity of 6PPD and 6PPD-q to soil and organic matter under different environmental conditions.
- The half-life of both parameters in soil and sediment as well as 6PPD-q in water.
- The reaction dynamics of 6PPD transforming into 6PPD-q.
- The prevalence of the contaminants in the dissolved phase compared to that adhered to particles.
- The lethality of 6PPD-q for fish related to particle size distribution and either attached to particles or dissolved phases.

Chapter 3. Anticipated Fate and Unmitigated Transport

Summary and Synthesis of Current Knowledge - A literature search was conducted to identify articles and studies with information about 6PPD and 6PPD-q sources and their anticipated fate, and unmitigated transport to determine how they get into and move through the MS4 system. Literature was located by reviewing databases and search engines that included Web of Science, PubChem, Science Direct, European Chemicals Agency (ECHA), and Google Scholar. Ecology also provided a compilation of articles, memos, and reports that covered these topics as well. 18 studies had relevant information. Of the 18 studies, 13 focused on transport in the environment.

Findings Summary **-** The following information was identified through the review of sources.

- The primary pathway of 6PPD-q transport is most likely via runoff from roads and parking areas to BMPs or through conveyance systems (storm drainpipes and catch basins) to surface waters or direct discharges to surface waters.
- 6PPD-q and other chemicals associated with tire wear particles (TWPs) are present in roadway runoff and in surface waters near highways, particularly in urbanized areas. However, more TWPs are found on roads and roadside ditches compared to receiving water columns or sediments.
- TWPs smaller than 10 μm tend to be air borne with larger TWP deposited onto and along roadways.
- Snow melt contains relatively high concentrations of 6PPD and 6PPD-q.
- Conflicting research has been reported regarding the temporal distribution of 6PPD-q and other TWP contaminants during a wet weather event. Some studies have reported that 6PPD-q transport exhibits a first flush phenomenon while other studies indicate tire wear chemicals concentrations peak several hours after the wet weather event starts, suggesting that these chemicals are transport-limited rather than mass-limited.
- The peak concentration of some tire wear chemicals may be delayed at a site due to many factors such as distance to the source(s), the type of source and its hydraulic behavior (e.g., stormwater outfall, drains from retention basins, drains from bridges) and or the extent of road traffic from which the chemical originates.

Knowledge Gaps **-** The main gaps in the fate and transport of 6PPD and 6PPD-q are as follows.

- Most studies have been conducted during wet weather events and less is known about the impact of 6PPD-q and other TWP contaminants that are deposited on roadways and accumulate during dry weather until the next runoff event. Research is needed to examine 6PPD-q deposition, how long it remains bioavailable and toxic, and how it's transported outside of wet weather events. This is particularly important in Washington State with a long dry summer season on the west side and semi-arid environments on the east side.

- Some key chemical properties of 6PPD-q (e.g., half-life on surface roads and partitioning to soils) are still uncertain.
- Better information is needed to determine the deposition of TWP in all sizes from dust via air deposition to larger particles thrown from tires onto the roadside: what is the distribution of these particles and what are their effects on fate and transport of the particles and 6PPD and 6PPD-q to surface waters?
- The temporal distribution of 6PPD-q and other TWP contaminants in the stormwater system and delivery to water bodies during wet weather events is poorly understood; we need to study 6PPD-q transport dynamics at different distances from roadway sources.

Chapter 4. BMP Evaluation Process

Development of the BMP Evaluation Basis **-** Two categories of BMPs were identified: Stormwater Flow and Treatment BMPs and Source Control BMPs. An evaluation criteria and process were developed to rank BMPs (Table 1.1) in terms of potential ability to provide treatment or prevent 6PPD and 6PPD-q from mixing with stormwater. The evaluation criteria are based primarily on treatment processes provided by the BMP and likely to reduce 6PPD and 6PPD-q. These treatment processes were identified after reviewing literature on physicochemical properties and lab or field testing of a BMP or as defined in stormwater manuals. The evaluation process included applying the criteria to an inventory of BMPs from 8 stormwater design manuals nationwide and BMPs approved through TAPE to identify which are most likely to reduce 6PPD and 6PPD-q from entering stormwater runoff.

Table 1.1 BMP Evaluation Criteria for 6PPD and 6PPD-q

Treatment or Prevention Potential Category	Flow and Treatment BMPs Definition of Category	Source Control BMPs Definition of Category
High	Dispersion, Infiltration, or some biofiltration BMPs (that use bioretention soil media or compost) where the underlying soils meet soil suitability criteria, or BMPs that provide the treatment process sorption.	BMP separates a source (i.e., roadway, parking, etc.) from stormwater.
Medium	BMPs provide sedimentation (removal depending on size/detention time) or filtration (removal depending on size of particles). May need a polishing layer/treatment train including sorption; i.e., sand filter with zero valent iron in layers.	BMP partially separates 6PPD and 6PPD-q from stormwater (i.e., E&O efforts); prevents 6PPD and 6PPD-q from entering stormwater from a minor source (i.e., traffic at a construction site)
Low	BMP does not provide infiltration, sorption, filtration, or sedimentation.	BMP is unlikely to provide any measurable separation between 6PPD and stormwater.

Findings Summary **-** The BMP evaluation criteria was applied to 93 flow and treatment BMPs and 84 source control BMP that were identified in the stormwater design manuals. For flow and treatment BMPs, 28 BMPs ranked high, 51 medium, and 14 low. For source control BMPs 9 ranked high, 3 medium, and 72 low. A complete list of the BMP evaluated along with the assigned rank is in Appendix 4-1.

Knowledge Gaps **-** Based on knowledge gaps from Chapters 2 and 3, these gaps were identified for better understanding the most effective flow and treatment BMPs and source control BMPs:

- Whether and what types of sorption remove 6PPD and 6PPD-q from stormwater.
- Whether 6PPD and 6PPD-q will remain adhered to soil or organic matter and not be exported to groundwater or downstream when stormwater flows over the soil.
- Whether infiltration, dispersion, and some biofiltration BMPs (that use bioretention soil media or compost), or BMPs that provide sedimentation and filtration will capture the particle sizes containing the most readily bioavailable concentrations of 6PPD and 6PPD-q.
- Whether the estimated half-lives of 6PPD and 6PPD-q are reliable and can be used to determine which BMPs are able to hold the contaminants until the concentrations are no longer lethal.
- Effectiveness or role of source control BMPs in preventing 6PPD or 6PPD-q transport to or on the roadways or in the stormwater system and ultimately to receiving waters.

Chapter 5. Research Prioritization

This chapter summarizes the research needs identified in each chapter into a one page table. Research needs are also prioritized as having a high, medium, or low need for the research to be conducted with the highest need focusing on understanding what BMPs would capture/contain/treat the contaminants and the potential impact on surface waters if current knowledge is inaccurate or incomplete. The categories were developed using best professional judgement guided by input from the project advisory committee. The next section provides a summary of the future research recommendations that were identified.

Recommendations for Future Research

- Additional testing is needed to determine if leaching of 6PPD and 6PPD-q will occur (and under what conditions) while adhered to soil, engineered materials, and organic matter. This property has a large impact on the fate and transport of the contaminants within the built environment including whether BMPs would permanently remove the contaminants or whether groundwater could be impacted by the contaminants.
- Study the chemical properties of 6PPD and 6PPD-q to better determine the half-life in different sectors of the environment (soil, water, sediments), within stormwater BMPs, and the toxicity/bioavailability in those forms. Fate of these chemicals in the environment will highlight where to focus our efforts to reduce their impacts on salmon and potentially other aquatic life.
- Whether transport in the dissolved phase, adhered to particles (or both) produces loadings of environmental concern and what phase or range of particle sizes containing or attached to 6PPD and 6PPD-q need to be removed by BMPs to reduce the lethality of stormwater effluent. This will help to understand loading of 6PPD and 6PPD-q from roadways and parking lots and which BMPs will be the most effective at filtering solids with 6PPD-q attached.
- Study the location and concentration of TWP throughout the roadway infrastructure system (driving surfaces, gutters, roadsides, snow or ice piles from winter plowing operations, catch basins and pipe sediments) to determine which operation and maintenance activities or changes will most effectively reduce loading.
- Determine what land uses (e.g., road traffic counts, industrial or commercial areas, various residential types, etc.) and specific locations near roads and parking areas might trigger the greatest need for treatment BMPs. Also assess if there is a traffic count (average daily traffic or ADT) threshold where 6PPD and 6PPD-q concentrations are no longer present in lethal amounts. This information will help to prioritize locations for BMPs.

- Study the relationship of time or seasons on 6PPD and 6PPD-q concentrations in wet weather events to better characterize these discharges. This could lead to BMPs that target the part of the storm that has the highest concentrations of these chemicals.
- Other tire-derived sources of 6PPD and 6PPD-q such as runoff from athletic fields with artificial turf, junk yards, auto repair shops, and tire stores should be investigated to see if they are sources for 6PPD and 6PPD-q to receiving waters. Other 6PPD-containing products beyond tires will likely be discovered.
- Perform field testing on BMPs that provide infiltration, dispersion, and biofiltration or sedimentation and filtration BMPs to assess whether these BMPs will capture the particle sizes associated with the most readily available concentrations of 6PPD and 6PPD-q, thereby reducing the lethality of the effluent.
- Determine loading from construction sites, particularly sites located on or adjacent to highways, to assess the priority of treating runoff from the sites as well as determine the most effective construction source control and flow and treatment BMPs. Construction sites can be active for years, during which time permanent stormwater BMPs in the construction area may be either offline or removed. As such, construction BMPs may be the only stormwater controls in place, and it is important to know whether 6PPD and 6PPD-q are present in runoff from a construction site in lethal amounts and whether the construction BMPs are able to reduce the lethality of the stormwater.
- Test various sorption media to understand whether this treatment process how best to utilize this treatment process in flow and treatment BMPs to remove 6PPD and 6PPD-q.
- Determine how long particles containing or with 6PPD attached will generate 6PPD-q at different stages of transport. The time the chemicals persist in the built environment will highlight where to focus efforts to reduce impacts on salmon and potentially other aquatic life.
- Perform field testing to understand fate and transport of 6PPD-q under environmental conditions other than wet weather events. Specifically, how long does 6PPD-q remain bioavailable and toxic in dry conditions and how is it transported outside of wet weather events. Fate and transport outside of wet weather events will be particularly important during dry seasons, dry periods, or in areas with semi-arid climates.
- Quantify reduction of 6PPD and 6PPD-q from pollutant generating surfaces (roadway or parking surfaces) to stormwater infrastructure by source control BMPs. This will help to prioritize efforts by municipalities and other organizations to reduce impacts to salmon and potentially other aquatic life.

CHAPTER 2: KEY PHYSICOCHEMICAL PROPERTIES FOR STORMWATER MANAGEMENT

2.1 Chapter Purpose

The intent of this chapter is to synthesize the current knowledge and understanding of the physicochemical properties of 6PPD and 6PPD-q. Specifically, how information was developed (i.e., laboratory testing, modeling, etc.), and where gaps in understanding exist. What is known about these pollutants' properties is used in Chapter 3 to evaluate human activities that may be sources, land uses, and potential reservoirs, which are locations where contaminants can be held before mobilizing to or within the MS4, for urban, urbanizing, or rural environments. Chapter 4 evaluates BMPs for their ability to capture, contain, and treat 6PPD and 6PPD-q based on these same physicochemical properties.

2.2 Overview of Chapter Contents and Work Completed

The work completed as part of this chapter included a compilation of 14 different sources of information for physicochemical properties of 6PPD and 6PPD-q and synthesis summarized in Tables 2.1 and 2.2. The sources reviewed were identified by the project advisory committee, and primarily consisted of model data or a combination of information from models and lab or field testing *(Chemaxon, n.d.; ECHA, 2021; National Center for Biotechnology Information, 2021; OECD, 2004; U.S. EPA, 2021a)*. The following is a breakdown of what was found:

- Seven of the 14 sources referenced modeled properties or a combination of model and lab or field data.
- One peer-reviewed journal article was also identified that summarized model data, as well as one unpublished Screening Information Data Set (SIDS) Initial Assessment Report, which was developed using data from the SIDS database[1].
- Three peer-reviewed journal articles provided data from studies performed in laboratories.
- One published report providing a synthesis of literature and a peer-reviewed journal article regarding data collected in the field were also synthesized.

Of the sources synthesized, most (9 of 14 sources) included physicochemical properties for 6PPD but not 6PPD-q. These nine sources represent a mix of lab, field-collected, and model-derived information. Three sources, including data from two models and a peer-reviewed journal article which referenced model data, reported physicochemical properties of both 6PPD and 6PPD-q. Two recent peer-reviewed journal articles summarizing studies performed in laboratories reported physicochemical properties of only 6PPD-q. It is important to note that the contaminant 6PPD-q was recently identified (in 2020), whereas 6PPD has been studied for decades for its use in tires. The higher number of sources for 6PPD resulted in a larger amount of reported physicochemical properties for 6PPD compared to 6PPD-q, as discussed in the following section.

2.3 Findings Summary

This section summarizes what is known about the physicochemical properties of 6PPD and 6PPD-q. The sources for this information along with the reported values are summarized in Tables 2.1 and 2.2. Appendix

[1] The Screening Information Data Sets (SIDS) Program involves the Organization for Economic Cooperation and Development (OECD) OECD countries collecting existing information and conducting tests on the allocated high production volume (HPV) chemicals following the protocol agreed upon by OECD.

Table A2.1 contains the physicochemical properties of common chemicals found in stormwater along with the properties of 6PPD and 6PPD-q defined in this section to provide a reference.

2.3.1 Density, Solubility, and Polarity

Physicochemical properties reported for 6PPD indicate the contaminant has a density similar to water, a relatively low solubility in water, and a tendency to adhere to soil or organic matter particles. Densities reported for 6PPD range from 0.995 to 1 g/mL (Table 2.1). The maximum solubility reported for 6PPD in the synthesized sources was 2.84 mg/L, with most sources reporting a solubility closer to 1 mg/L. The densities and solubilities reported suggest that 6PPD is likely to remain undissolved for an unspecified amount of time and will float if it is not attached to another particle. Klöckner et al. (2020) reported the concentration of 6PPD adhered to fine particle sizes in roadway sediment. The study sieved all runoff sediments to focus on smaller particle sizes (<500 µm) and found that 6PPD concentrations were highest in the less than 20µm and 50 to100µm particle size ranges. It is important to note that the study excluded larger particles potentially common in roadway sediments, and that larger particle sizes may contribute 6PPD and 6PPD-q to stormwater infrastructure. The density of the roadway sediment was also reported, with almost all of the samples having a density of 1.3 g/mL or higher, and most of the samples having a density above 2.3 g/mL. The higher density may suggest that 6PPD, when attached to roadway sediment particles, may be denser than water, and as such is likely to settle in laminar or less turbulent flow environments where the samples were collected (street sweeper material, underground vaults, settling ponds and lakes).

As mentioned previously, physicochemical properties were less frequently reported for 6PPD-q in field studies. The density was not reported in the sources synthesized in Table 2.2. The solubility of 6PPD-q appears to be higher than 6PPD in water, with reported values of 51 to 67 mg/L. This suggests 6PPD-q may be more likely to travel in the dissolved phase than 6PPD.

2.3.2 Volatility and Bioconcentration

Volatility of the contaminants was assessed through Henry's law constant and the vapor pressure. The estimated Henry's law constant for 6PPD is 7.43 X 10^{-4} at 25 °C suggesting that it has a moderate potential to volatilize from surface waters (OSPAR Commission, 2006). The vapor pressure for 6PPD and 6PPD-q are reported to be low, 6.85 X 10^{-3} Pa at 25°C and 6.57 X 10^{-6} Pa at 25°C, respectively, suggesting they are not likely evaporate at 25°C (77°F). However, due to the tendency for 6PPD to sorb to soil, sediments, and suspended particulates (see Section 2.3.3), 6PPD can be present on suspended particles in the air (OSPAR Commission, 2006).

The bioconcentration factor of a contaminant provides an estimate of the potential for bioaccumulation from exposure in water. 6PPD has a calculated bioconcentration factor range of approximately 349 (Arnot-Gobas Method; US EPA, 2021b) to 801 (BCFWIN v2.15; OSPAR Commission 2006); this range suggests it has a low to moderate potential for bioaccumulation in aquatic organisms (OSPAR Commission, 2006). At the time of this report, additional data was in the process of being published for the bioconcentration factor of 6PPD (U.S. EPA, 2021a). . 6PPD-q has a calculated (Arnot-Gobas Method) bioconcentration factor of 131.9 (US EPA, 2021b), which suggests it has a low potential for bioaccumulation in aquatic organisms.

2.3.3 Melting Point, Water Partition Coefficient (K_{ow}), Organic Carbon Water Partition Co-Efficient (K_{oc})

6PPD and 6PPD-q share some similar physicochemical properties which may inform how long the contaminants persist and how they move through the built environment. High melting points (up to 121.5°C for 6PPD, 169.18°C for 6PPD-q) were reported for both contaminants, which indicates they will likely not melt in the built environment. Additionally, both contaminants have a relatively high log K_{ow} (4.68 to 5.6 for 6PPD and 3.25 to 5.5 for 6PPD-q) and log K_{oc} (4.04 to 4.84 for 6PPD and 3.94 for 6PPD-q) which suggests affinity for soil and organic matter. This would also suggest that 6PPD and 6PPD-q adhered to soil would not leach from the soil particles and enter groundwater, however, additional research is needed to confirm the tendency to adhere and stay adhered to particles under environmental conditions (Sections 2.4 and 2.5).

While 6PPD and 6PPD-q appear to have an affinity to soil or organic matter, both contaminants are moderately non-polar compounds which indicates that transport of the contaminants in the dissolved phase is possible, but not anticipated to be probable. This is supported by Fugacity Model[2] results: a higher percentage in the environment is predicted to adhere to soil and sediment (approximately 90% for both 6PPD and 6PPD-q), though approximately 10% is anticipated to not adhere to soil and remain in the water column (U.S. EPA, 2021b). No lab or field data were reviewed to indicate the prevalence of contaminants in either phase, which is discussed further in Section 2.4.

2.3.4 Degradation

From within a tire rubber matrix (including a tire wear particle), 6PPD will continue to bloom to the surface until there is no more 6PPD remaining in the rubber matrix. Additionally, as long as 6PPD is in the presence of ozone or oxygen, it will form a variety of transformation products, including 6PPD-q. The following paragraphs discuss the half-lives of both contaminants in different media and potential methods of degradation in the environment.

The degradation of 6PPD and 6PPD-q will likely vary based on the medium and environmental and physical conditions (e.g., temperature, pH, presence of metals, etc.). The estimated half-lives of 6PPD and 6PPD-q are 75 days in soil and 337 days, in sediment (meaning soils below water) are based on Fugacity Model results (U.S. EPA, 2021b). No other sources reported on the half-lives in sediment or soil.

Many more sources (model, lab, and field data) reported on the half-lives of 6PPD and 6PPD-q in the water column. In water, reported half-lives for 6PPD range from around 3 hours to less than a day (OSPAR Commission, 2006; ECHA, 2021), with shorter half-lives noted in warmer waters and those containing heavy metals (OSPAR Commission, 2006). However, long-term stability up to four weeks has been noted in cold conditions at a pH of 2 (OSPAR Commission, 2006). The half-life of 6PPD-q in water is less certain: results from the Fugacity Model indicate the half-life is 900 hours (U.S. EPA, 2021b), whereas other sources report the half-life as longer than 6PPD or more specifically at least one day (Tian, 2021). Additional research is needed to better understand the half-lives of both 6PPD and 6PPDq in Washington's environments. More discussion about this is included in Sections 2.4 and 2.5.

Degradation of 6PPD and 6PPD-q is expected to result from a combination of abiotic and biotic processes (OSPAR Commission, 2006; ECHA, 2021). When on a surface, such as a tire, 6PPD absorbs UV-B

[2] Fugacity Models are utilized to study and predict the behavior of chemicals in different environmental media,

radiation and is also expected to undergo rapid direct photolysis (OSPAR Commission, 2006) in direct sunlight (OECD, 2004). Moreover, 6PPD is used in tires for its reactivity, to neutralize ozone, and to a lesser extent oxygen (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Reemtsma, 2022). It is therefore expected that 6PPD on a tire or other surface would degrade in the presence of ozone or oxygen. In the atmosphere, 6PPD undergoes indirect photodegradation via rapid reaction with hydroxyl radicals. Photodegradation is also likely a predominant mechanism for 6PPD loss in surficial soils (OSPAR Commission, 2006).

Environmental degradation is presumed to be largely abiotic for 6PPD, as it is highly reactive and not reported to be readily biodegradable. In an OECD TG 301C test on ready biodegradability, based on biochemical oxygen demand, only approximately 2% of 6PPD was biodegraded; however, based on high-performance liquid chromatography, approximately 92% of 6PPD was removed within 28 days indicating that 6PPD was transformed (OECD, 2004). Moreover, 6PPD degradation was tested in an algae nutrient medium containing traces of ions of heavy metals such as manganese, cobalt, copper, molybdenum, and zinc to represent environmental conditions, and reported results indicated the half-life was decreased compared to tests on 6PPD in a buffered aerobic solution. Aside from the expectation that 6PPD-q is also expected to be degraded by a combination of abiotic and biotic processes (OSPAR Commission, 2006; ECHA, 2021), no lab or field data were reported which indicated methods of degradation of 6PPD-q.

Table 2.1. 6PPD Physicochemical Properties

Physico-Chemical Properties	(National Center for Biotechnology Information, 2021)	(U.S. EPA, 2021a)	(U.S. EPA, 2021b)	(Klöckner P. , et al., 2020)	(OSPAR Commission, 2006)	(ECHA, 2021)	(Chemaxon, n.d.)	(Cheng, et al., 2007)	(Williams, et al., 2017)	(Tian Z. , et al., 2020)	(OECD, 2004)	(Hiki, et al., 2021)	(BUA, 1998)	(Bayer AG, 1997)
Density	1.02 g/ml (8.51 lb/gal)				0.995 g/cm^3 (62.1 lb/ft^3) at 50°C (122ºF)									0.995 g/cm^3 (62.1 lb/ft3) at 50ºC (122ºF)
Molecular Weight	268.4 g/mol (0.5917 lb/mol)				268.5 g/mol (.5919 lb/mol)									
Water Solubility	<1 mg/ml (<8.35 X 10^{-3} lb/gal) at 15.6ºC (60°F)		2.84 mg/l (2.37 X 10^{-5} lb/gal) at 25°C (77ºF)		1 X 10^{-3} g/l (8.35 X 10^{-6} lb/gal) at 20°C (68ºF)	0.001 mg/ml (8.35 X 10^{-6} lb/gal) at 50°C (122ºF)					1 mg/l (8.35 X 10^{-3} lb/gal) at 20°C (68ºF)			
Log K_{ow}			4.68	4.68	4.68		4.91	5.6					5.4	
Log K_{oc}	4.84		4.36		4.84				4.04					
Boiling Point	260ºC (500ºF) at 760 mm Hg (14.7 Psi), calculated 370°C (698ºF)	260ºC (500ºF) at 760 mm Hg (14.7 Psi), calculated 354-412°C (669-774ºF)	369.67°C (697.41ºF)		230ºC (446ºF) at 1013 hPa (14.7 Psi)								230°C (446ºF) at 13.33 hPa (0.1933 Psi)	
Henry's Law Constant					7.43 X 10^{-4} at 25ºC (77ºF)									
Bioconcentration Factor					801									
Half-Life			75 days in soil & 337 days in sediments[1]		Less than a day in water; 3 hrs in warmer water containing heavy metals; up to 4 weeks in cold water pH=2									
Melting Point	45-50°C (113-122ºF)		121.5°C (250.7 ºF)		45-48°C (113-118.4ºF)								45-48°C (113-118.4ºF)	
Vapor Pressure	Negligible at 25°C (77°F)		6.85 X 10^{-3} Pa (9.94 X 10^{-7} Psi); 6.129 X 10-7 atm-m^3/ mole (using VP of 4.93 X 10^{-6} mm Hg (9.53 X 10^{-8} Psi) WS of 2.84 mg/l (2.37 X 10^{-5} lb/gal))		6.85 X 10^{-3} Pa (9.94 X 10^{-7} Psi) at 25°C (77°F)						6.85 X 10^{-5}hPa (9.94 X 10^{-7} Psi)			

1. Fugacity Model Results

Table 2.2. 6PPD-q Physicochemical Properties

Physicochemical Properties	(National Center for Biotechnology Information, 2021)	(U.S. EPA, 2021a)	(U.S. EPA, 2021b)	(Klöckner P. , et al., 2020)	(OSPAR Commission, 2006)	(ECHA, 2021)	(Chemaxon, n.d.)	(Cheng, et al., 2007)	(Williams, et al., 2017)	(Tian Z. , et al., 2020)	(OECD, 2004)	(Hiki, et al., 2021)
Density												
Molecular Weight			298.39 g/mol (0.6578 lb/mol)									
Water Solubility			51.34 mg/l (4.28 X 10^{-4} lb/gal) at 25°C (77ºF)									67 +/- 5 ug/l (5.59 X 10^{-7} lb/gal) at pH 8 and 23°C; 73.4ºF) (dechlorinated water)
Log K_{ow}			3.98				3.24	4.1		5-5.5		
Log K_{oc}			3.94									
Boiling Point			430.19°C (806.34ºF)									
Henry's Law Constant												
Bioconcentration Factor												
Half-Life			75 days in soil & 337 days in sediments[1]; 900 hrs in water[1]							At least 1 day in water		
Melting Point			169.18°C (336.52ºF)									
Vapor Pressure			6.57 X 10^{-6} Pa (9.53 X 10^{-10} Psi); 3.77 X 10^{-10} atm-m3/mole (using VP of 4.93 X 10^{-8} mm Hg (9.53 X 10^{-10} Psi) and WS of 51.3 mg/l (4.28 X 10^{-4} Psi))									

1. Fugacity Model Results

2.4 Research Gaps and Assumptions Made

Data obtained from studies conducted in the laboratory or in the field (no model data) composed a smaller fraction of sources synthesized. While modeled physicochemical properties provide information about the contaminants, the lack of lab and field testing is limiting because it does not account for all interactions in a natural environment. The model data is presented in Tables 2.1 and 2.2 as it was the only information available for some of the properties of 6PPD and 6PPD-q. The assumption made for this project is that the specific values for modeled half-lives are accurate and are needed for the following Chapters estimations for fate and transport.

Specific research gaps identified during the review of sources included:

- While the log K_{ow} and log K_{oc} for 6PPD and 6PPD-q (OSPAR Commission, 2006) suggest a tendency for the contaminants to adhere to soil or organic matter, no studies were identified that tested in the laboratory or field whether the contaminants would remain adhered to soil or organic matter. It was assumed for the study that both contaminants would remain adhered and not leach.
- The half-lives of 6PPD and 6PPD-q in sediment in water and soil included in this report are based on Fugacity Model results (U.S. EPA, 2021b).
- Klöckner et al. (2020; 2021) studied concentration and density of road and tunnel sediment with limited particle size ranges of <20 to 500um, virtually no information on 6PPD concentrations was found for larger road dirt or tire wear particulates. 6PPD-q was not evaluated in the report and no additional information was found in other sources regarding the particle size or density of 6PPD-q attached to particles. More information is needed to characterize tire wear particles sizes found in the roadway environment, what is typically transported during storm events, and the lethality of different particle sizes to aquatic species.
- Although 6PPD reactivity is high, it is not presumed to all become 6PPD-q (Hu X. , et al., 2022), even though many of the reaction dynamics are unknown.
- Fugacity model results indicate transport of 6PPD and 6PPD-q is likely in both the dissolved phase as well as adhered to particles. No lab or field data was available on the prevalence of contaminants in either phase. Additionally, no information on how quickly 6PPD or 6PPD-q would adhere to soil or organic matter particles if released into the environment as an individual particle or dissolved particle. Work in the following chapters presume the contaminants are travelling in both phases (dissolved and attached to particles).

2.5 Recommendations for Next Steps and/or Additional Research

Recommendations for next steps and additional research are based on the goals of the project as well as the research gaps described in Section 2.4. The recommendation includes some of the physicochemical properties that will be important to verify through lab and field testing, to better understand the fate and transport of the contaminants as well as what treatment mechanisms will capture, contain, or treat 6PPD and 6PPD-q. The following bullets describe each recommendation for next steps and additional research:

- *Confirm preference to adhere to soil and organic matter* – Additional lab and field testing is needed to confirm leaching of 6PPD and 6PPD-q from soil and organic matter is not likely, and to understand any conditions where it could occur. This property has a large impact on the fate and transport of the contaminants within the built environment and would indicate whether groundwater could be impacted by the contaminants

- *Confirm the half-life of 6PPD and 6PPD-q in soil, water, and sediment in water* – Additional lab and field testing is needed to confirm the values produced by the Fugacity Model and the half-life of 6PPD-q, as these values impact the persistence of 6PPD and 6PPD-q in the environment. The lab and field testing may also inform the methods of how 6PPD and 6PPD-q are degraded in the built environment.
- *Understand the density of 6PPD and 6PPD-q in different phases* – Additional lab and field testing is needed to understand the density of both contaminants when dissolved, adhered to a soil or organic matter particle, or attached to a tire wear particle near the source. This data is needed to understand which BMP treatment mechanisms will be most effective.
- *Understand in which phase (dissolved or adhered to particles) 6PPD and 6PPD-q are typically transported* – Lab or field testing is needed to understand in which phase the contaminants are typically transported. Additionally, information regarding the rate that 6PPD or 6PPD-q would adhere to soil or organic matter particles is needed to understand which BMP treatment mechanisms will be most effective.
- *Characterize the amount of 6PPD in fugitive tire particles (all sizes) in the roadway environment*. It will also be important to understand the sizes of particles that are commonly transported to the storm system or to water bodies.
- *Understand the particle size distribution of roadway particles* – This data is needed to understand what particle sizes are captured by flow and treatment BMPs and the potential to remove 6PPD-q from stormwater. It will also be important to understand the lethality of different particle sizes, to ensure BMPs target particles which would be lethal to aquatic species.

Appendix 2-1

Table A2.1. Physicochemical Properties of Common Chemicals Found in Stormwater

Chemical	Mass (g/mol)	Log Kow	Koc (ml/g)	Water Solubility (mg/L) at 25oC	Henry's Law Constant (atm-m3/mole)	Vapor Pressure (mmHg)
Acetone	58.08	-0.24[b]	6.69[a]	miscible[b]	3.50E-05[a]	232[a]
Methyl Ethyl Ketone	72.11	0.2[b]	17.5[a]	256,000[b]	5.69E-05[a]	90.6[a]
Phenol	94.11	1.47[b]	26.9[a]	77,900[b]	3.33E-07[a]	0.35[a]
Dimethyl phthalate	194.19	1.70[b]	39.8[a]	4,160[b]	*7.60E-08*[a]	3.08E-03[a]
Benzene	78.11	2.05[b]	83[b]	1,770[b]	5.55E-03[a]	94.8[a]
Toluene	92.14	2.58[b]	117[a]	546[b]	6.64E-03[a]	28.4[a]
Ethylbenzene	106.17	3.11[b]	170[a]	181[b]	7.88E-03[a]	9.6[a]
o-Xylene	106.17	3.11[b]	178[a]	221[b]	5.18E-03[a]	6.61[a]
2,4,5-T	255.48	3.40[b]	97.7[a]	273[b]	*2.99E-09*[a]	3.75E-05[a]
Parathion	291.26	3.43[b]	7,751[b]	24.0[b]	2.98E-07[a]	6.68E-06[a]
Cyclohexane	84.16	3.44[b]	*531*[a]	59.3[b]	0.150[a]	96.9[a]
Naphthalene	128.17	3.51[b]	1,300[b]	31.9[b]	4.40E-04[a]	8.50E-02[a]
Lindane	290.81	3.76[b]	1,480[a]	7.30[b]	3.18E-06[a]	4.20E-05[a]
6PPD-Q	298.39	3.98[c]	8,589[c]	51.3[c]	3.77E-10[c]	4.93E-08[c]
Pentachlorophenol	266.32	4.41[b]	20,000[a]	14.0 (at 20ºC)[b]	2.45E-08[a]	1.10E-04[a]
Phenanthrene	178.23	4.52[b]	22,400[a]	1.09[b]	4.23E-05[a]	1.21E-04[a]
6PPD	268.40	4.68[c]	*11,000*[a]	1.9[c]	*7.69E-08*[a]	*1.88E-07*[a]
Aldrin	364.90	5.17[b]	410[b]	0.011[b]	4.40E-05[a]	1.20E-04[a]
Pyrene	202.26	5.32[b]	73,350[b]	0.134[b]	1.19E-05[a]	4.50E-06[a]
Chrysene	228.29	5.71[b]	*157,000*[a]	0.0033[b]	5.23E-06[a]	6.23E-09[a]
PCB 1254	326.40	6.31[b]	42,500[d]	0.011[b]	2.83E-04[d]	6.86E-05[d]

a. Values are from CompTox Chemicals Dashboard (Experimental Average where possible; italicized if a Predicted Average).
b. Values are from *Hazardous Wastes: Sources Pathways Receptors*, by Richard J. Watts (1998).
c. Values are from EPA EPI Suite (average of values if multiple given).
d. Values are from Pubchem (average of values if multiple given).

CHAPTER 3: ANTICIPATED FATE AND UN-MITIGATED TRANSPORT

3.1 Chapter Purpose

The intent of this chapter is to synthesize the current knowledge and understanding about 6PPD and 6PPD-q sources and their anticipated fate and un-mitigated transport to determine how they get into and move through the MS4 system. This information was used to prioritize where flow and treatment BMPs should be located. For this study, only tire wear sources were considered and discussed in this chapter. Discussion is also provided regarding research gaps, proposed next steps and additional research needed to close the gaps.

3.2 Overview of Chapter Contents and Work Completed

A literature search was conducted to identify articles and studies that mentioned 6PPD and/or 6PPD-q on several databases and search engines that included Web of Science, PubChem, Science Direct, European Chemicals Agency (ECHA), and Google Scholar. Ecology provided a compilation of articles, memos, and reports that covered these topics as well. For this chapter, we reviewed the articles and reports on the origins, fate, and transport of 6PPD and 6PPD-q in the environment. 18 studies had relevant information for this section and are listed in the references. Of the 18 studies, 13 focus on transport in the environment and are summarized in Table 3.1. The results of this review are highlighted in Appendix 3-1 and further discussed in this document.

3.3 Findings Summary

3.3.1 Sources

Tire particles on roadways come in all sizes from full tires, large parts of tires when delamination or blowouts occur, down to very small particles, between 5 μm to 300 μm with an abundance reported between 70-80 μm (Kreider, Panko, McAtee, Sweet, & Finley, 2010; Wagner, et al., 2018), caused by wear between the tire and road surface. During typical tire wear, small (<10 μm; clay to fine silt size) tire wear particles (TWPs) are emitted into the air and larger TWPs (>10 μm), which make up the majority of TWPs, are deposited onto road surfaces (Wagner, et al., 2018). The smallest of the deposited TWPs may become trapped in asphalt pavement or transported by stormwater runoff into soils, storm sewers, and surface waters, where they can continue to leach their chemical constituents into the surrounding environment (Kole, Löhr, Van Belleghem, & Ragas, 2017; Saifur & Gardner, 2021). Larger particles can remain on the roadside for long periods until they are picked up by litter crews or sweeping operations. All these particles will likely keep exuding 6PPD and 6PPD-q until they are removed from the environment or the 6PPD in the rubber compound is exhausted.

TWPs contain many chemicals and several researchers have reported highest concentrations in tire leachate and in field studies of roadway runoff for HMMM 1,3-DPG, 2-OHBT (a byproduct of the vulcanization accelerator 2-mercaptobenzothiazole) and the cyclic amines 1-cyclohexyl-3-phenylurea (CPU) and 1,3-dicyclohexylurea (DCU) (Saifur & Gardner, 2021). These are commonly used additives in tire manufacturing, with up to 14% of the initial tire mass attributable to these compounds, accounting for up to 2.8 lbs released into the environment per tire (Unice, Bare, Kreider, & Panko, 2015) based on an average passenger tire mass of 20 lbs (Lee, Ju, & Kim, 2020). In Europe, new vehicle tires contain up to 1 to 2% (10,000-20,000 μg/g) of 6PPD (OSPAR Commission, 2006). Thus, while 6PPD-q is now known to be a toxicant to aquatic life at low concentrations, the effects of mixtures of chemicals in roadway runoff from tires, including 6PPD and 6PPD-q, are not known.

Several studies have demonstrated that 6PPD-q, and other chemicals associated with TWPs, are present in roadway runoff and in surface waters near highways, particularly in urbanized areas (Peter, et al., 2018; Tian, et al., 2022; Challis, et al., 2021; Johannessen C. P., Helm, Lashuk, Yargeau, & Metcalfe, 2021). While the parent chemical 6PPD (from which 6PPD-q is formed) is used in many types of applications to help rubber products (e.g., transmission belts, hoses, automotive mounts and bushings, and other mechanical products) resist degradation and cracking (Wagner, et al., 2018; Krüger, Boissiere, Klein-Hartwig, & Kretzschmar, 2005), current research suggests that the primary source of 6PPD-q is from tire wear on roadways (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022; Saifur & Gardner, 2021; Challis, et al., 2021). To the extent that TWP concentrations are indicative of relative concentrations of 6PPD, Wagner, et al. (2018) in their review show that far higher concentrations of TWPs have been found on road surfaces and roadsides than in either the water column or stream sediments. This may indicate that stormwater BMPs located adjacent to road surfaces or just the roadside soils and vegetation are filtering out TWPs and preventing them from reaching surface waters. Additional discussion on this topic is included in Section 3.5.

3.3.2 Fate

Information regarding fate and transport of 6PPD-q in aquatic systems has been primarily derived from laboratory studies examining leaching of TWPs using various methods that are intended to simulate potential environmental fate in the field. Knowing the properties that influence chemical fate water solubility, octanol water partition coefficient (log K_{ow}), and organic carbon partitioning coefficient (log K_{oc}) as discussed in Chapter 2, and how 6PPD-q interacts with the terrestrial and aquatic environment, indirectly provides useful information regarding potential transport mechanisms of 6PPD-q and other TWP chemicals. The degree to which bound 6PPD or 6PPD-q in sediments (below water) can become bioavailable to aquatic biota via biotic and/or abiotic transformation processes is not known.

3.3.3 Transport

Much of our knowledge regarding transport of 6PPD-q has been derived from recent field studies in which street dust, and stream or stormwater samples were collected and analyzed over different seasons, multiple years, and/or different precipitation and hydrologic conditions. The literature review in support of this chapter identified several journal articles and reports that examined stream sites in the Toronto metro area (e.g., (Johannessen C. P., Helm, Lashuk, Yargeau, & Metcalfe, 2021)), Saskatoon, Canada (Challis, et al., 2021), Washington State (Peter, et al., 2020), Germany (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022), China (Huang, et al., 2021), and Australia (Rauert, et al., 2022); Table 3.1). The following summarizes information derived from these studies regarding the fate and transport of 6PPD-q. We also highlight critical data gaps identified by various researchers.

Currently, the believed primary pathway of 6PPD-q transport is via runoff from roads and parking areas with tire wear to surface waters. Limited research suggests that treated wastewater discharges are a minor source of either 6PPD or 6PPD-q (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022). Urbanized or urbanizing areas are particularly prone to wet weather runoff of TWPs and associated chemicals due to the relatively high percentage of untreated impervious surface area and high vehicle traffic and associated TWPs (Wagner, et al., 2018; Challis, et al., 2021; Baensch-Baltruschat, Kocher, Stock, & Reifferscheid, 2020). At the time this report was written, a limited number of studies comparing concentrations of 6PPD-q in streams with different types of surrounding land uses indicate lower concentrations of 6PPD-q in less urbanized areas (Challis, et al., 2021).

Studies have demonstrated the occurrence of many potential contaminants in leachate from tires in addition to 6PPD-q and it appears likely that 6PPD-q is not the only potential hazard to aquatic life (Challis, et al., 2021; Rauert, et al., 2022). However, thus far, it appears that 6PPD-q is the most toxic chemical in TWP leachate to Coho salmon adults (McIntyre & Kolodjiez, 2021) and juveniles (Tian Z. , et al., 2020) but not some other species of aquatic life (Hiki, et al., 2021; Varshney, Gora, Siriyappagouder, Kiron, & Olsvik, 2022). The few comparative aquatic toxicity studies examining different commonly reported TWP contaminants (e.g., DPG) suggest that they may be less toxic to aquatic life than 6PPD-q (Hiki, et al., 2021). Brinkmann et al (2022) investigated the acute toxicity of 6PPD-q to rainbow trout, brook trout, arctic char, and white sturgeon and reported 96-hr acute toxicity thresholds (LC50) of 1.0 ug/L or less for the two trout species. Tian et al (2022) reported a revised juvenile Coho salmon LC50 < 0.1 ug/L, indicating substantial sensitivity to 6PPD-q.

3.3.4 Sampling Methods and Stormwater Timing

Few studies have examined fate and transport of 6PPD-q under environmental conditions other than wet weather events. Until recently, analyses of 6PPD-q had not been reported in studies of TWP (Tian Z. , et al., 2021 ; Tian, et al., 2022; Johannessen & Parnis, 2021). While some differences in analytical methods are being used by different researchers to study 6PPD-q in samples, it appears that quality control in these studies (e.g., precision, percent recoveries, blanks) is satisfactory and detection limits are low enough to reliably compare results across studies. However, there needs to be better harmonization of the source of 6PPD-q used in toxicological studies and as standards for characterizing performance of analytical methods used to quantitate 6PPD-q in stormwater studies.

A study by Challis et al (2021) examined concentrations of 6PPD-q and other tire wear associated chemicals at stormwater outfalls and stream sites along the South Saskatchewan River, Canada that are influenced to varying degrees by road runoff. They sampled several of these sites under different storm events and seasons. The highest concentration of 6PPD-q was recorded during a June wet weather event that had more precipitation than other sampling events in that study (24mm or 0.95in) and a longer dry period preceding the wet weather event. In that study, sampling locations nearest to residential areas and roadways had higher concentrations of 6PPD-q than sites associated with less urbanized and rural land uses. Other studies have been concerned with potential accumulation of 6PPD-q on roadsides during dry weather which may then result in higher concentrations of 6PPD-q during runoff events (Peter, et al., 2020; Department of Toxic Substance Control, Safer Consumer Products, & California EPA, 2021). Although these authors did not examine specific toxicants such as 6PPD or other tire wear chemicals, they noted that more urbanized basins may accumulate sufficient toxicants on roadways over relatively short periods of time, thereby minimizing the influence of antecedent dry intervals. As noted previously, chemical properties of 6PPD-q (e.g., half-life on surface roads and partitioning to soils) are still uncertain (Unice, Bare, Kreider, & Panko, 2015; Tian Z. , et al., 2020). Better quantitative information would help inform the influence of air deposition of TWP dust and dry weather deposits of 6PPD-q on fate and transport to surface waters.

Though unclear currently, 6PPD-q and other TWP contaminants may be deposited on roadways where they may accumulate during dry weather until the next runoff event (Huang, et al., 2021). However, a study by Feist et al (2017), comparing the relationship between stormwater runoff and observed Coho salmon mortality in urbanized versus less developed basins in the Puget Sound region, noted that cumulative precipitation appears to be a factor only in less urbanized basins and not related to Coho mortality in the most urbanized areas (Feist, et al., 2017). This is an active area of research. Another mechanism by which 6PPD-q and other TWP contaminants may be stored temporarily is in snow or ice that is plowed from roadways (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022; Challis, et al., 2021). These studies reported that snowmelt contained relatively high concentrations of these contaminants. This is consistent with other pollutants such as hydrocarbons, metals, solids, nutrients, and chlorides that accumulate in snow piles and are subsequently released in high concentrations during snowmelt (Oberts, 1994).

Several researchers have examined the temporal distribution of 6PPD-q and other TWP contaminants during a wet weather event. Some studies indicate evidence of a first flush phenomenon, whereby the peak concentration of 6PPD-q occurs soon after the onset of wet weather runoff (Johannessen, Helm, & Metcalfe, 2021). For some other tire wear chemicals in roadway runoff, such as the corrosion inhibitor (benzotriazole, 5-methylbenzotriazole, OH-BTH) and the vulcanization accelerator (1,3-diphenylguanidine, DPG), a local study in an urban creek showed that the peak concentration may occur several hours after the wet weather event started (Peter, et al., 2020). Peter et al (2020) suggested that in urban creeks, many of the roadway runoff chemicals examined may be transport-limited rather than mass-limited. Meaning that there is ample contaminant to mobilize and that the limiting factor is the runoff flow to transport it. As a result, the peak concentration of some tire wear chemicals may be delayed due to factors such as distance to the source(s), the type of source and its hydraulic behavior (e.g., stormwater outfall, drains from retention basins, drains from bridges) and or the extent of road traffic from which the chemical originates. Few studies are available thus far that have examined transport dynamics of 6PPD-q in particular, and how factors such as watershed size, time of concentration, traffic behaviors, land cover, and sources affect transport observed concentrations of 6PPD-q in stormwater discharges and to particular stream reaches.

3.4 Research Gaps; Triggers for Treatment BMPs, and Prioritization of Treatment

3.4.1 Research Gaps

Several research gaps were identified in the fate and transport of 6PPD and 6PPD-q which include:

- Some key chemical properties of 6PPD-q (e.g., half-life on surface roads and partitioning to soils) are still uncertain.
- Better information is needed to determine the deposition of TWP dust particles through air deposition and larger particles thrown from tires onto the roadside. What is the distribution of these particles and what are their effects on fate and transport of the particles and 6PPD and 6PPD-q to surface waters?
- The temporal distribution of 6PPD-q and other TWP contaminants in the MS4 and in receiving waters during wet weather events are poorly understood currently. While a few research studies suggest that 6PPD-q transport exhibits a first flush phenomenon, other studies indicate tire wear chemical concentrations peak several hours after the wet weather event starts, suggesting that all these chemicals are transport-limited rather than mass-limited. Studies are needed that examine 6PPD-q; transport dynamics using sites at different distances from roadway sources, time of concentration, concentrations during the entire hydrograph in different storm events and different preceding precipitation histories (e.g., extent of dry period prior to the storm event).
- Few studies have examined fate and transport of 6PPD-q under environmental conditions other than a handful of wet weather events internationally. Research is needed to determine 6PPD-q deposition, how long it remains bioavailable and toxic, and how it's transported outside of wet weather events. This is particularly important in Washington State with a long dry summer season on the west side and semi-arid environments on the east side of the mountains.

3.4.2 Figure 3.1 an Illustration of Fate and Transport: Unknown and Knowns

The flow chart in Figure 3.1 illustrates what is known and unknown about the fate and transport of 6PPD and 6PPD-q. The chart shows three potential pathways that these contaminants might travel through the MS4 starting with the source and ending with discharges via infiltration or to surface waters. The symbols on the chart represent the following items:

- Source (oval): Roadway runoff is the only source considered in this report
- Pathway (rectangles): The contaminants are carried by three common stormwater pathways: soil/biofiltration BMPs, roads and hard surfaces, and stormwater conveyance such as pipes and ditches.
- Unanswered questions (diamonds): are inserted in the flow chart in the appropriate spots.
- The "known" properties of 6PPD and 6PPD-q from studies and models (polygons): The properties identified by models are identified with an asterisk.

3.4.3 Assessing Available 6PPD and 6PPDq Information with Existing Triggers for Runoff Treatment

What is known about 6PPD and 6PPDq sources and its anticipated fate and unmitigated transport through the MS4 system were reviewed for comparability with the triggers for identifying when and where runoff treatment is needed based on guidance in the Ecology and WSDOT stormwater manuals. The goal was to assess potentials triggers for providing 6PPD and 6PPD-q treatment and consider how that information aligns with the current triggers for providing treatment in the stormwater manuals. Figure 3.2 shows the runoff treatment targets and applications for roadway projects from the WSDOT Highway Runoff Manual (WSDOT, 2019). The requirements shown in this table are the same as the requirements in the Ecology Stormwater manuals; however, the Ecology Stormwater manuals have additional requirements for Enhance Treatment[3].

The literature suggests that highly urbanized areas are the most likely areas to generate TWP and thus 6PPD and 6PPD-q toxic concentrations; however, it is unknown what land uses and level of Average Daily Traffic (ADT) it takes to reach that concentration. Both Enhanced Treatment and Oil Control Treatment requirements shown in Figure 3.2 depend on ADT, vehicle size, and traffic patterns. It is assumed that similar parameters could be used to determine when treatment BMPs for 6PPD and 6PPD-q would be required. For instance, low speed turning movements, like those in parking lots, likely produce more TWP residue than higher speed movements around curves. Similarly, intersections controlled by stop lights might have more TWP residue than similar intersections where the main route is free moving and the side routes are controlled by stop signs. The roadway speeds and ADT likely play a role at intersections as well. A roadway with a high ADT likely has higher concentrations of TWP, 6PPD, and 6PPD-q than roads with lower ADTs. Further, research and monitoring are needed to determine which land uses and ADT levels cause 6PPD and 6PPD-q levels to reach levels of concern in roadway runoff.

3.4.4 Prioritize Treatment

[3] The SWMMWW and Municipal Permit also include the following sites as requiring Enhanced Treatment.
a. discharge directly to fresh waters designated for aquatic life use or that have an existing aquatic life use; or
b. discharge to conveyance systems that are tributary to fresh waters designated for aquatic life use or that have an existing aquatic life use; or
c. infiltrate stormwater within ¼ mile of a fresh water designated for aquatic life use or that has an existing aquatic life use.

Based on what we know about roadways and TWP production and concentrations, consideration for prioritizing placement of treatment BMPs is shown in Figure 3.3 which illustrates several pathways to receiving waters. Based on what is known about 6PPD and 6PPD-q and stormwater management, BMPs should be located as close to sources as possible. Given the unknowns related to dry periods, and possible atmospheric transport and deposition during those periods, fate and transport of those particles further from their source may call for other locations of BMPs.

3.5 Recommendations for Next Steps and/or Additional Research

The recommendations for next steps and additional research are as follows.

- *Study the chemical properties of 6PPD-q to better determine half-life in different sectors of the environment (soil, water, sediments) and the toxicity/bioavailability in those forms*. Fate of these chemicals in the environment will highlight where to focus our efforts to reduce their impacts on salmon and potentially other aquatic life.
- *Study the location and concentration of TWP in the environment* (e.g., roadway surfaces, gutters, roadsides, snow or ice piles from winter plowing operations, catch basin and pipe sediments) to determine which operation and maintenance activities or changes will most effectively reduce loading.
- *Study the relationship of time or seasons on 6PPD and 6PPD-q concentrations in wet weather events to better characterize these discharges*. This could lead to BMPs that target the part of the storm that has the highest concentrations of these chemicals.
- *Study the location and loading of 6PPD and 6PPD-q to determine what land uses*, e.g., ADT, industrial or commercial, residential density, etc, *will trigger the need for treatment BMPs*.
- *It is anticipated that other product sources beyond tires will be discovered*. Other sources such as runoff from athletic fields with artificial turf, junk yards, and auto repair shops and tire stores should be investigated to see if they are sources for 6PPD and 6PPD-q.

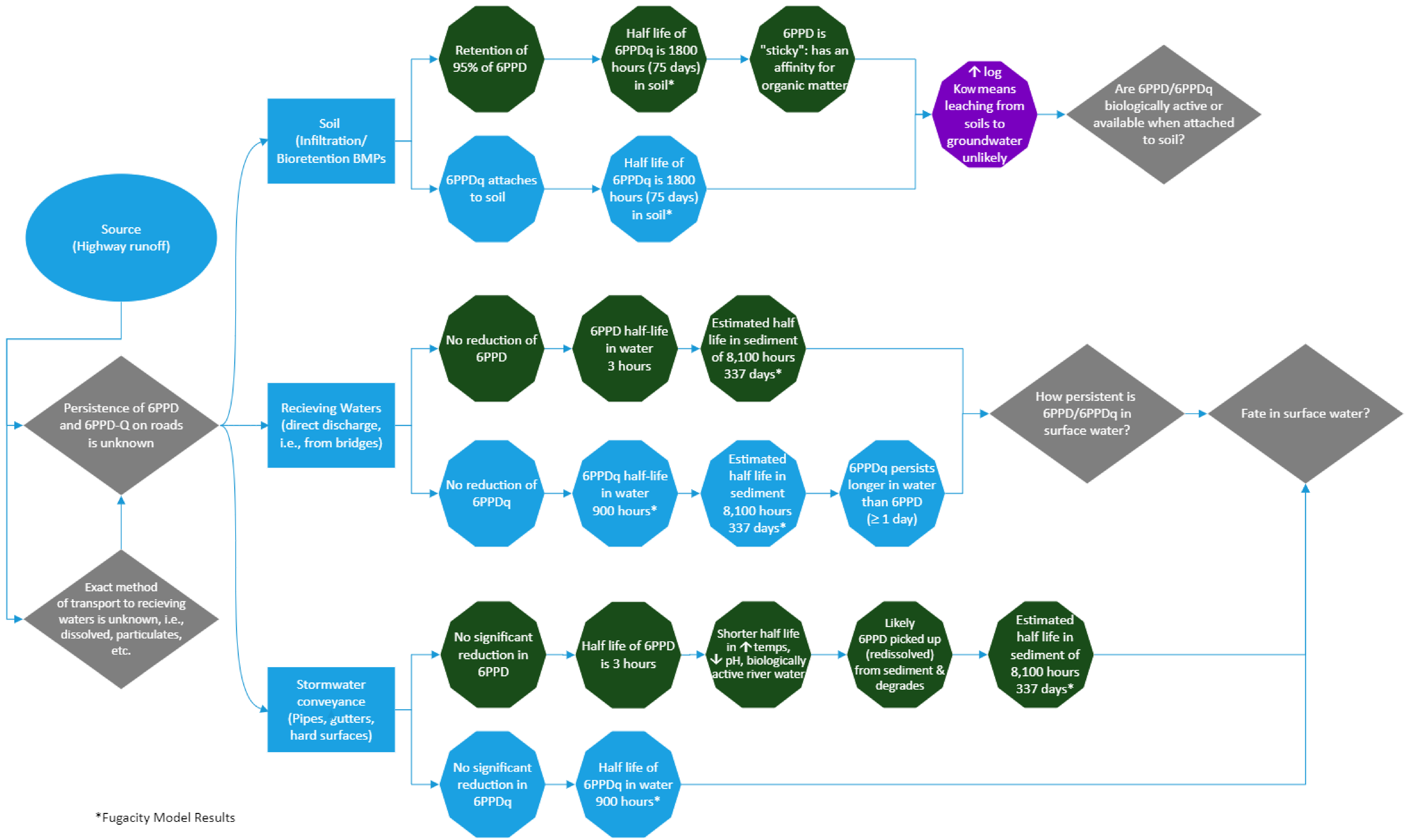

Figure 3.1. Visualization about what is known and unknown regarding the fate and transport of 6PPD and 6PPD-q

Table 3-1 Runoff treatment targets and applications for roadway projects.

Treatment Target	Application	Performance Goal
Basic Treatment	All project TDAs where runoff treatment threshold is met or exceeded. Table 3 2 identifies receiving waters that only require Basic Treatment for direct discharges.	80% removal of total suspended solids (TSS)
Enhanced Treatment (dissolved metals)	Same as for Basic Treatment AND does not discharge to Basic Treatment receiving water body (listed in Table 3-2) AND 1. Roadways within *Urban Growth Areas* (UGAs): • Fully controlled or partially controlled limited access highways with a design year ADT[1] ≥ 15,000 OR • All other roadways with a design year ADT[1] ≥ 7,500 OR 2. Roadways outside of UGAs: • Roads with a design year ADT ≥ 15,000 3. Required by an Ecology-approved Basin Plan or TMDL, as described in Sections 2-4.2 and 2-4.7.	Provide a higher rate of removal of dissolved metals than Basic Treatment facilities for influent concentrations ranging from 0.005 to 0.02 mg/L for dissolved copper and 0.02-0.3 mg/L for dissolved zinc
Oil Control	Same as for Basic Treatment AND 1. There is an intersection with existing ADTs where either ≥15,000 vehicles (ADT) must stop to cross a roadway with ≥25,000 vehicles (ADT) or vice versa[2] excluding projects proposing primarily pedestrian or bicycle improvements OR 2. Rest areas with an expected trip end count greater than or equal to 300 vehicles per day[3] OR 3. Maintenance facilities that park, store, or maintain 25 or more vehicles (trucks or heavy equipment) that exceed 10 tons gross weight each[3] OR 4. Eastern Washington roadways with ADT >30,000.	No ongoing or recurring visible sheen and 24-hr average total petroleum hydrocarbon concentration of not greater than 10 mg/L with a maximum of 15 mg/L for a discrete (grab) sample
Phosphorus Control	Same as for Basic Treatment AND the project is located in a designated area requiring phosphorus control as prescribed through an Ecology-approved Basin Plan or TMDL.[4]	50% removal of total phosphorus (TP) for influent concentrations ranging from 0.1 to 0.5 mg/L TP

[1] The design year ADT is determined using Chapter 1103 of the WSDOT Design Manual.

[2] Treatment is required for these high-use intersections for lanes where vehicles accumulate during the signal cycle, including through, left-turn lanes, and right-turn lanes. If no turn pocket exists, the treatable area must begin at a distance equal to three car lengths from the stop line. If runoff from the intersection drains to more than two collection areas that do not combine within the intersection, treatment may be limited to any two of the collection areas where the cars stop. See HRM FAQ for additional information.

[3] For rest areas and maintenance facilities, oil control BMPs are required for the PGIS subject to the oil control threshold activities listed in Table 3-1. All-day parking areas do not require oil control. Oil Control BMPs must be sized to treat all water directed to them.[4] Contact the RHE or environmental staff to determine whether phosphorus control is required for a project.

Figure 3.2. Runoff Treatment Targets, Source: WSDOT 2019 Highway Runoff Manual

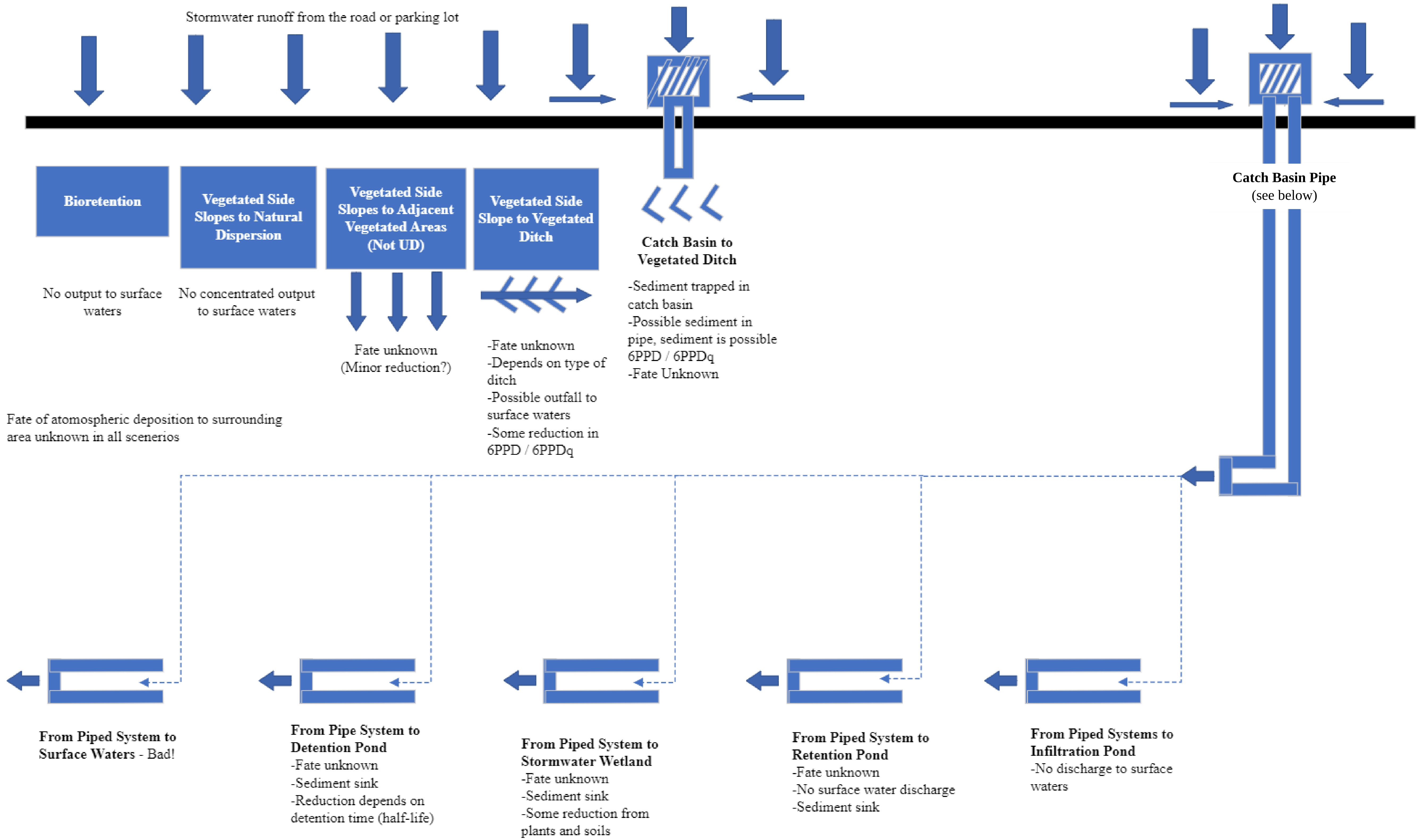

Figure 3.3. Fate and Transport of 6PPD through MS4

Appendix 3-1

Table A3.1 Summary of Fate and Un-Mitigated Transport Key Information

Reference	City/Locale	Type of Sites Sampled (Stormwater Outfalls, Streams, etc.)	Timing of Samples (Seasons, Months)	Tire Wear Chemicals Measured (6PPD-q, others if appropriate)	Range of Concentrations Reported for Each Chemical	Notes
(Johannessen, Helm, & Metcalfe, 2021)	Greater Toronto Area in Ontario, Canada	samples were collected from two rivers adjacent to high traffic highways.	October 2019 - March 2020 (Fall and Winter)	HMMM	0.4 ug/L - 2.08 ug/L	Raw data were not presented in this study, however separate data tables were reference. The max concentration value was specifically mentioned in text, but the min value in this table was estimated from a bar graph presented in the paper. Samples were collected hourly in 300-mL aliquots over a 42-h period, with three aliquots included in each bottle, representing a 3-h composite sample.
(Peter, et al., 2020)	Puget Sound, Washington, USA	Miller Creek, a representative small, urban watershed in the Puget Sound region.	07/26/2018 - 12/12/2018 (Summer/Fall/Winter)	HMMM	0.005 Mass Load (g/day at baseflow) - 0.160 Mass Load (g/day at baseflow)	To assess water quality during summer/early fall baseflow conditions, on July 26, August 15, and September 18, 2018, 12 h time-weighted composite samples were collected via ISCO sampler. Further compositing enabled replicate extractions. Storm hydrograph sampling used composite and grab samples before, during, and after (~48 h/ event) storm events on October 26, November 2, and December 11, 2018. Complementary grab samples during November and December provided coverage during composite sampling gaps due to equipment malfunctions. Grab samples were collected in October because high flows washed away the ISCO sampler.
(Johannessen C. P., Helm, Lashuk, Yargeau, & Metcalfe, 2021)	Greater Toronto Area, Canada	Both sites are within land-use areas with a high degree of urbanization (≥85%) and both rivers discharge into the nearshore zone of western Lake Ontario	July and August 2020 and August 2021	DPG	Mean Values = 0.76 +/- 0.05 ug/L (grab sample, Highland Creek, July 2020) and 0.16 +/- 0.03 ug/L (composite sample, August 2020)	Investigated contaminant contributions of both highways and WWTPs (Don River only during dry period to ensure no interference from highway runoff)
(Johannessen C. P., Helm, Lashuk, Yargeau, & Metcalfe, 2021)	Greater Toronto Area, Canada	Both sites are within land-use areas with a high degree of urbanization (≥85%) and both rivers discharge into the nearshore zone of western Lake Ontario	July and August 2020 and August 2021	HMMM	Mean Values = 10 ug/L (includes HMMM and its TPs and a precursor compound, Highland Creek and Don River, July 2020, grab sample), 2.3 ug/L (Highland Creek, grab sample, one significant pulse), 6.8 ug/L (Don River, composite sample, July 2020), and 18 ug/L (Highland Creek, composite sample, July 2020)	Investigated contaminant contributions of both highways and WWTPs (Don River only during dry period to ensure no interference from highway runoff)
(Johannessen C. P., Helm, Lashuk, Yargeau, & Metcalfe, 2021)	Greater Toronto Area, Canada	Both sites are within land-use areas with a high degree of urbanization (≥85%) and both rivers discharge into the nearshore zone of western Lake Ontario	July and August 2020 and August 2021	6PPD-q	Mean Value = 0.72 +/- 0.26 ug/L (grab sample, Highland Creek, July 2020), 0.54 +/- 0.04 ug/L (grab sample, Don River, July 2020), and 0.21 +/- 0.02 ug/L (composite sample, August 2020)	Investigated contaminant contributions of both highways and WWTPs (Don River only during dry period to ensure no interference from highway runoff)
(Department of Toxic Substance Control, Safer Consumer Products, & California EPA, 2021)	California, USA	NA	NA	6PPD	< 23 ng/g - 1.9 ug/g in road dust and up to a max of 0.11 ug/L in stormwater	This was a draft chemical profile for the California Department of Toxic Substances Control to consider identifying the product chemical 6PPD as a Priority Product. It summarizes available literature and discusses the applicability to the state of California. Report includes a detailed summary of a 2011 Swedish Summary applicable to fate and transport.

Reference	City/Locale	Type of Sites Sampled (Stormwater Outfalls, Streams, etc.)	Timing of Samples (Seasons, Months)	Tire Wear Chemicals Measured (6PPD-q, others if appropriate)	Range of Concentrations Reported for Each Chemical	Notes
(Department of Toxic Substance Control, Safer Consumer Products, & California EPA, 2021)	California, USA	NA	NA	6PPD-q	1 ug/L - 6.1 ug/L in stormwater runoff and surface water	This was a draft chemical profile for the California Department of Toxic Substances Control to consider identifying the product chemical 6PPD as a Priority Product. It summarizes available literature and discusses the applicability to the state of California. Report includes a detailed summary of a 2011 Swedish Summary applicable to fate and transport.
(Challis, et al., 2021)	Saskatoon, Canada	South Saskatchewan River stormwater outfalls, snow dumps, and river water samples with different mixes of residential, industrial, and retail development	June, July, August (summer) 2019; June, August October 2020	6PPD-qu; DPG, DCA, DCU, CPU	6PPD-q: 0 - 1400 ng/L in stormwater samples; snowmelt concentration 2-8-fold greater	Concentration highest in association with the highest precipitation event which was preceded by a long dry period. DPG concentrations > DCU > CPU > 6PPD-Q > DCA
(Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022)	Leipzig, Germany	Snow from urban streets and influent and effluent from a WWTP connected to a combined sewer system during snow melting event	February (winter)	6PPD ozonation products including the quinone	WWTP influent: 0.105±0.037 ug/L WWTP effluent: < 25 ng/L dry weather: < 25 ng/L	Snow samples used to identify different degradation products of 6PPD and 6PPD-q; many degradation products identified; half-life of 6PPD-q in drinking water reported to be 33h at room temp (Hiki et al 2021); 6PPD-q subject to additional degradation in the presence of oxidants
(Rauert, et al., 2022)	Brisbane Australia	stormwater near Freeway and other roads	June and October	6-PPD-Q, HMMM, DPG, several benzothiazoles, benzotriazoles, aromatic amines	6-PPD-Q: 0.39 - 88 ng/L	higher concentrations of all TWP chemicals in October sampling; DPG highest6 in concentration> HMMM > 2-OHBT > CPU > DCU More frequent and larger precipitation events in October; concentrations peaked at the beginning or during the storm event but remained elevated at the end of the storm compared to baseflow concentrations. Settled TWPs may be a continuing source of chemicals into the urban creek post storm
(Johannessen & Parnis, 2021)	Greater Toronto Area, Canada	A highly urbanized watershed in close proximity to several major multi-lane highways	NA	6PPD-q	0.30 ± 0.01 ug/L - 2.30 ± 0.05 ug/L	Target compounds were analyzed using ultra-high pressure liquid chromatography with high resolution mass spectrometric detection with parallel reaction monitoring.
(Johannessen & Parnis, 2021)	Greater Toronto Area, Canada	A highly urbanized watershed in close proximity to several major multi-lane highways	NA	DPG	Max = 0.22 ± 0.07 ug/L	Target compounds were analyzed using ultra-high pressure liquid chromatography with high resolution mass spectrometric detection with parallel reaction monitoring.
(Wagner, et al., 2018)	NA	NA	NA	TWP	400-2200 mg/g in river sediments, acute effects of 25 - 100000 mgP/L, chronic effects of 10 - 3600 mg TWP/L, and sublethal effects of 500 - 500000 mg TWP/L	This is a review paper; thus, no actual data were collected and no samples were taken.

Chapter 4: BMP Evaluation Process

4.1 Chapter Purpose

The intent of this chapter is to characterize the likely efficacy of existing BMPs to reduce concentrations of 6PPD and 6PPD-q in stormwater runoff. Gaps in available information from Chapters 2 and 3 are described along with how the gaps influenced the BMP evaluation process. The chapter concludes with recommendations for additional research specific to gaps in understanding the efficacy of BMPs and prioritization of where to locate BMPs.

4.2 Overview of Chapter Contents and Work Complete

An evaluation process was developed to rank flow, treatment, and source control BMPs in terms of their potential ability to reduce 6PPD and 6PPD-q. The evaluation process is a qualitative system that uses defined high, medium, and low categories to rate the BMPs treatment potential. For each category, an evaluation criterion was defined using information collected from literature regarding the physicochemical properties of the contaminants and results from lab or field testing of BMPs (Chapter 2). The evaluation criterion focuses on the capture or treatment processes that would likely reduce (flow and treatment BMPs) or prevent (source control) 6PPD and 6PPD-q from entering stormwater. As part of the category definition, assumptions and unknown information were also identified.

The evaluation process focuses on the full range of particle sizes in which 6PPD and 6PPD-q may be present in the built environment from full tires to TWP down to 10µm as discussed in Chapter 3. For all sizes of TWP, 6PPD is expected to bloom to the surface until there is no more 6PPD remaining in the rubber matrix. As such, the BMP evaluation process was developed to consider the differences in particle sizes received or encountered by source control BMPs and flow and treatment BMPs. For example, smaller particle sizes (less than 500 µm[4]; medium sand size and smaller) include suspended (<25 µm) and settleable solids (>25 µm), which can be transported by most storm events and most likely to reach stormwater infrastructure and receiving waters or flow and treatment BMPs. Particles between 500µm to 4750µm (coarse sand to fine pebbles) typically settle in catch basins, pretreatment BMPs, or may be too dense to be transported by smaller storm events. Particles larger than 4750 µm (medium pebbles to cobbles, floatables, debris, larger TWP) may remain on or along the roadway surfaces, move down embankments, or if they are transported with stormwater, can clog storm drain inlets, build up in storm infrastructure, or over time can reduce the infiltration capacity of flow and treatment BMPs (by clogging the surface layer). Large material is not typically transported by stormwater except for infrequent, larger storm events. Preventing the pebble or cobble sized particles (4750µm or larger) from entering MS4 infrastructure may be addressed more effectively by source control BMPs. Figure 4.1 illustrates the different particle sizes present on roadways.

An inventory of BMPs was compiled which included flow, treatment, and source control BMPs identified from the Table 4.1 stormwater design manuals as well as BMPs approved through the TAPE program. Each BMP was assigned a potential treatment category that indicates whether the BMP appears to have a high, medium, or low potential to reduce 6PPD or 6PPD-q. The following sections describe the basis for the evaluation criteria and the findings of the evaluation process.

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[4] 500 µm is considered the largest size for TSS as part of the TAPE Program (Washington State Department of Ecology, September 2018).

Clay	< 3.9 µm
Silt	3.9 to 62.5 µm
Very Fine Sand to Medium Sand	62.5 to 500 µm
Coarse Sand to Fine Pebbles	500 to 4750 µm
Pebbles to Cobbles, Floatables, & Debris	> 4750 µm

Figure 4.1 Common Stormwater Particle Sizes

Table 4.1 Stormwater Design Manuals Reviewed

Jurisdiction	Year	Title
Caltrans	2019	Stormwater Quality Handbook: Project Planning and Design Guide
District of Columbia	2020	Stormwater Management Guidebook
State of Minnesota	2021	Minnesota Stormwater Manual
New York City	2015	New York City Stormwater Manual
Prince George's County, Maryland	2014	Stormwater Management Design Manual
State of Washington	2019	Stormwater Management Manual for Western Washington (SWMMWW)
State of Washington	2019	Washington State Department of Transportation (WSDOT) Highway Runoff Manual (HRM)
State of Indiana	2007	Indiana Storm Water Quality Manual

4.3 Findings Summary

This section describes the development of the evaluation criteria and findings of the BMP evaluation. The BMP evaluation criteria for high, medium, and low treatment potential categories are summarized in Tables 4.2 for flow and treatment BMPs and Table 4.3 for source control BMPs. Development of the criteria along with the assumptions and unknowns are discussed further in Sections 4.3.1 and 4.3.2. Results of the BMP evaluation, which included BMPs from 8 stormwater design manuals, are included in Section 4.3.3. In the context of this work, flow, treatment, and source control BMPs are defined as follows.

- **Flow and Treatment BMPs** are defined as physical, structural, or mechanical devices intended to limit pollutants from entering stormwater infrastructure by providing water quality or hydrologic benefit, using specific treatment process (WSDOT, 2019; Ecology, 2019). This includes both permanent structural BMPs as well as temporary construction runoff BMPs that are intended to remove particles/solids and other pollutants from stormwater. Examples of permanent structural BMPs include bioretention cells, infiltration ponds, and proprietary treatment devices approved by TAPE. Examples of construction runoff BMPs are silt fences, temporary sedimentation basins, and straw wattles. Construction BMPs are not anticipated to achieve the treatment performance goals of permanent structural BMPs; however, they are designed to reduce TSS and as a result were included with permanent flow and treatment BMPs.

- **Source Control BMPs** are practices meant to prevent the interaction of stormwater with pollutants through physical separation or management of activities that are sources of pollutants (WSDOT, 2019; Ecology, 2019). Examples of source control BMPs include education and outreach programs, operation and maintenance activities such as street sweeping or line cleaning, as well as construction source control BMPs, such as temporary stabilization or proper materials handling.

The number of unknowns and assumptions discussed in Chapters 2 and 3 as well as in this chapter resulted in an evaluation criterion that is similar between 6PPD and 6PPD-q whether bound or unbound to a particle. The only physicochemical property information available for both contaminants was log K_{ow} and K_{oc} data. While other physicochemical properties are available for 6PPD and 6PPD-q that are relevant to this work, no other properties were defined in the literature for both contaminants. To compensate for the missing information, it was assumed that the properties of the other contaminant were the same "ballpark" in order to develop the evaluation criteria. These unknowns and assumptions are described in Section 4.4.

Table 4.2 Flow and Treatment BMP Evaluation Criteria for 6PPD and 6PPD-q

Treatment Potential Category	BMP Evaluation Criteria Definition of Category
High	Dispersion, Infiltration, or some Biofiltration BMPs (that use bioretention soil media or compost) where the underlying soils meet the soil suitability criteria[5], or BMPs that provide the treatment process sorption.
Medium	BMPs that provide sedimentation (removal depending on size/detention time) or filtration (removal depending on size of particles). May need a polishing layer/treatment train including sorption, i.e., sand filter with zero valent iron in layers.
Low	BMP does not provide infiltration, sorption, filtration, or sedimentation.

Table 4.3 Source Control BMP Evaluation Criteria for 6PPD and 6PPD-q

Prevention Potential Category	Definition of Category
High	BMP separates a source (i.e., roadway, parking, etc.) from stormwater.
Medium	BMP partially separates 6PPD and 6PPD-q from stormwater (i.e., E&O efforts); prevents 6PPD and 6PPD-q from entering stormwater from a minor source (i.e., traffic at a construction site)
Low	Unlikely to provide any measurable separation between 6PPD and stormwater.

[5] The site suitability criteria (SSC) are set of requirements used to assess whether an infiltration BMP can be located at a site. SSC-6 identifies the physical and chemical properties needed in the native soils underlying a BMP to achieve treatment goals: cation exchange capacity ≥ 5 meq/100g dry soil, minimum 18-inch soil depth, 1% organic content, and the soil must not contain waste fill materials.

4.3.1 Flow and Treatment BMPs Categories

Flow and treatment BMPs were described by the primary treatment processes provided by BMP. These processes were identified based primarily on the physicochemical properties of 6PPD and 6PPD-q identified in Chapter 2. In addition, there are only two BMP studies that evaluated 6PPD and 6PPD-q removal and both were conducted in a lab as opposed to field testing (McIntyre, et al., 2015; McIntyre & Kolodjiez, 2021). Using treatment processes allowed for a high-level, direct comparison between BMPs. Since BMPs are included in this evaluation from outside of Washington, BMPs were grouped together by the same treatment processes, not necessarily by their names or design standard. The basis for each category is described in this section. A list of the BMPs evaluated along with the anticipated treatment processes and results of the evaluation are included in Appendix 4-1.

High Treatment Potential

BMPs and BMP processes identified with the highest potential to reduce 6PPD and 6PPD-q are infiltration, dispersion, and some biofiltration BMPs combined with sorption (particularly BMPs that contain bioretention soil media or compost). Reasons for selecting these BMPs and BMP process are as follows:

- Infiltration BMPs and Biofiltration BMPs that infiltrate reduce the volume of runoff and thereby the contaminant load carried to surface water. For both types of BMPs to be classified in the high category, the soil suitability criteria for physical and chemical properties (SSC-6) previously described, must be met.
- Research by McIntyre showed that stormwater passing through the Ecology 60:40 bioretention soil mix prevented pre-spawn mortality in coho salmon that was observed when coho salmon were exposed to untreated stormwater (McIntyre, et al., 2015).
- Initial lab testing conducted by McIntyre and Kolodjiez, indicates that bioretention media appears to remove 6PPD-q to below detection levels (McIntyre & Kolodjiez, 2021).
- Research conducted on Compost-Amended Biofiltration Swales (CABS) in the lab and at a field site off State Route 518 indicates that the BMP has a non-polar compound removal rate above 90% (Tian, et al., 2019). As 6PPD and 6PPD-q are moderately non-polar compounds (Chapter 2), similar removal rates are possible for the contaminants by CABS.
- The log K_{ow} and K_{oc} identified in the literature (Chapter 2) suggest that 6PPD and 6PPD-q tend to adhere to organic particles or organic matter. Because infiltration and bioretention BMPs are designed for stormwater to flow through soil or media, the contaminants are expected to remain fixed in the soil or media as stormwater infiltrates.

Assumptions and unknowns regarding the high potential category relating to the physicochemical properties of 6PPD and 6PPD-q (also discussed in Chapter 2) are as follows:

- No field testing has been performed to confirm that the contaminants will remain adhered when water from later storms flows through soil or organic matter.
- Removal of 6PPD and 6PPD-q by bioretention and infiltration BMPs were assumed to be the same, as the log K_{ow} and K_{oc} are similar for both contaminants and lab testing results were not available for removal of 6PPD and 6PPD-q by infiltration BMPs.

Assumptions and unknowns regarding the high potential category relating to the BMPs which provide the treatment process sorption to reduce 6PPD and 6PPD-q are as follows.

- The previously mentioned research on the effectiveness of bioretention indicates that sorption may be an effective removal method.
- There are contradictory findings regarding the type of sorption responsible for removal. The City of Tacoma was preparing samples for analysis and observed that when a solution of copper was added to samples with sulfur and 6PPD-q, that 6PPD-q was reduced to below detection levels. The city hypothesized that sorption may be responsible for removal of 6PPD-q or that 6PPD-q may be changing form (Bozlee, 2022). Whereas Tian et al. (2020) conducted column testing using a myriad of materials and chemicals that provide different treatment processes (i.e., filtration, cation/anion exchange, etc.) to remove 6PPD and 6PPD-q and no significant removal was measured. The results suggest that both contaminants were in a dissolved form and that neither cation nor anion exchange (forms of sorption) were responsible for removal.

Assumptions regarding the BMP design for high potential category involve whether particles can be suspended during a storm event, and whether the BMP is able to filter the size of particles necessary to remove 6PPD and 6PPD-q when adhered to soil or organic matter or contained in TWP. Specifically:

- In Ecology’s Stormwater Management Manuals (SWMM), BMP design guidance has been developed to limit re-suspension of particles and anoxic zones in BMPs during storm events (Howie, 2022). The assumption made for the BMP evaluation was that manuals developed by other organizations developed BMPs in their manuals similarly, and that particles already in the BMP would not be re-suspended and discharge from the BMP.
- Because of the contaminants affinity for soil and organic matter as well as the assumption that particles would not resuspend, it was assumed that dispersion, Infiltration, or biofiltration BMPs where the underlying soils meet soil suitability criteria (SSC6), or BMPs that provide the treatment process sorption would contain 6PPD and 6PPD-q for the duration of their half-lives. However, sedimentation or filtration BMPs are not designed to have a residence time equal or greater than the contaminants half-life and are not expected to provide sufficient time for the contaminant in the dissolved phase to decay. The half-life data identified in Chapter 2 was primarily from Fugacity Model Results which estimates the half-life in water to be 3 hours for 6PPD and 900 hours for 6PPD-q. The half-life for 6PPD and 6PPD-q in soils and sediment (soils in water) was estimated to at 75 days and 337 days respectively. Except for 6PPD in water, there are no BMPs which have a residence time equivalent to the half-life of 6PPD and 6PPD-q. Developing a better understanding of the half-lives are a research gap that is identified in each chapter.
- It was also assumed that infiltration captures the most tire particle sizes (that could fit through the typical catch basin grate) in the upper inches of the soil surface, and that unbound 6PPD and 6PPD-q are immediately sorbed onto nearby soil particles. It is assumed that a given tire will in the end eventually deliver the same amount of 6PPD, but that availability of 6PPD-q to be washed off is higher for smaller particle sizes if they haven’t already lost their 6PPD load from the tire matrix.
- At the time this report was written, it was assumed that infiltration, dispersion, and some biofiltration BMPs could remove particles from stormwater (<500um) including those with bound 6PPD and 6PPD-q. These assumptions also applied to BMPs with a medium potential to reduce the contaminants, as is described in the following paragraph.

Medium Potential

The BMPs identified with a medium potential to reduce 6PPD and 6PPD-q include BMPs which provide sedimentation and filtration treatment processes. Both processes provide treatment by capturing particles and for this assessment capturing particles refers to both TWP as well as other solids in stormwater runoff that may have bound 6PPD or 6PPD-q. With sedimentation, solids are removed from stormwater by settling whereas filtration removes solids by physically trapping or capturing them. For both treatment processes the particle size and density can affect removal with heavier and larger particles being more likely to be removed. Tire particles larger than fine silt (25 to 62.5 μm) are expected to be removed through sedimentation and filtration (up to 500 μm or medium sand size). Smaller tire wear or other stormwater solid particles (fine silts and clays) are not expected to be captured through filtration and sedimentation. However, these contaminants have a tendency to sorb to soil or organic matter which will increase the particle size and density. As such it was assumed that a portion of the smaller particles will be removed. For these BMPs, a polishing layer may be needed to fully remove 6PPD and 6PPD-q, as some 6PPD or 6PPD-q may exist in the dissolved fraction (McIntyre & Kolodjiez, 2021).

Low Potential

Any BMP processes (infiltration, sorption, or settling/sedimentation) which did not fall under the criteria defined for high or medium potential to reduce 6PPD or 6PPD-q were defined as BMPs or processes with a low potential to reduce these contaminants. BMPs that fall under this category may also include BMPs which cannot be located near a roadway or other source of 6PPD or 6PPD-q. No information was found during the review of sources on physiochemical properties indicating other stormwater treatment processes could reduce the contaminants.

Flow and Treatment BMP Examples

Examples of BMPs in the high, medium, and low treatment potential categories are summarized in Table 4.4 followed by an illustration of the BMP evaluation process in Figure 4.2. Proprietary and non-proprietary BMPs approved through the TAPE process also fall into these categories. BMPs approved by TAPE which function similar to infiltration or dispersion BMPs or biofiltration BMPs (that use bioretention soil media or compost) that infiltrate into underlying soils and meet SSC-6, as well as BMPs which provide sorption are expected to have a high treatment potential. TAPE BMPs which provide filtration or sedimentation without sorption are expected to provide a medium treatment potential. Information presented in the TAPE documents was used to determine which treatment mechanisms each of these BMP uses which are summarized in Appendix 4-1.

Table 4.4 Examples of Flow and Treatment BMPs by Treatment Potential Category

Treatment Potential Category	Examples of Flow and Treatment BMPs
High	Bioretention, Infiltration Basins, Media Filter Drain, Dispersion
Medium	Sand Filter, Detention Ponds, Permeable Pavements
Low	Perforated Stub-Out Connection, Vegetated Roofs, Tree Retention and Tree Planting

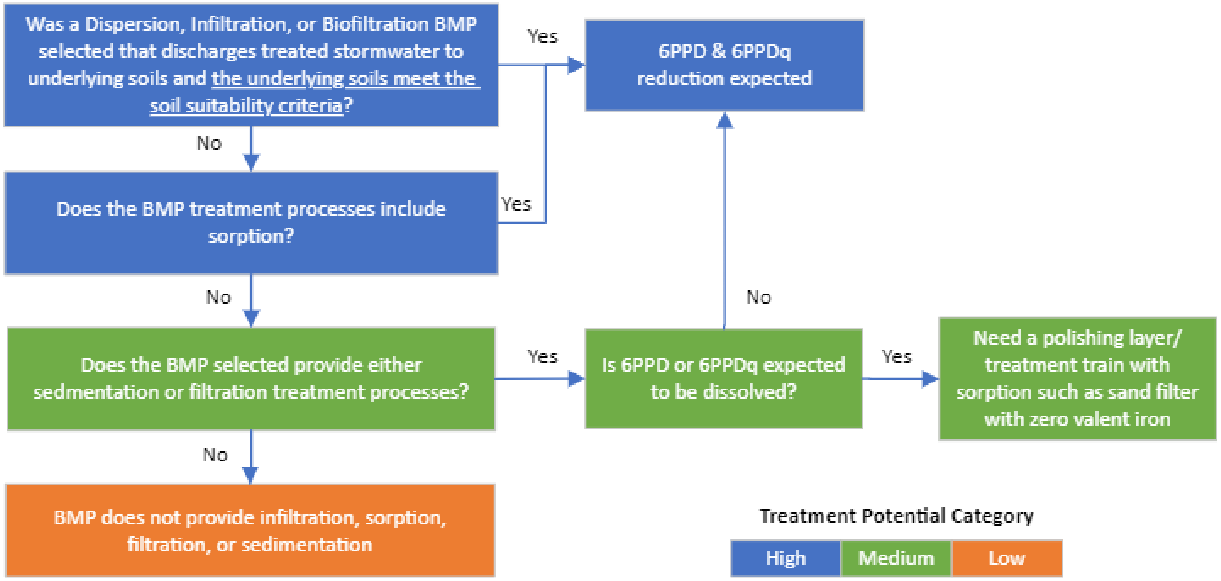

Figure 4.2 Flow and Treatment BMP Evaluation Process

<u>4.3.2 Source Control BMP Categories</u>

The criteria for source control BMPs was developed based upon preventing TWP from entering stormwater infrastructure or the physicochemical properties of 6PPD and 6PPD-q, particularly the tendency to adhere to soil particles or organic matter. No literature was identified which evaluated source control BMPs efficacy for preventing 6PPD or 6PPD-q from mixing with precipitation or stormwater. As a result, the evaluation criteria were assumed to be the same for 6PPD and 6PPD-q and do not incorporate basin-specific conditions. Typically, source control is basin-specific, meaning different results may be achieved depending on the number and type of roadways, land use, urban or rural, topographic, and other characteristics of the basin. Because no literature was identified which evaluated source control BMPs, the criteria was not able to incorporate basin-specific conditions.

Additionally, it is important to note that practices likely exist that are not currently listed as source control BMPs in stormwater design manuals which would prevent 6PPD and 6PPD-q from coming into contact with stormwater. For example, roadway clean-up crews which remove tires or strips of tire treads would remove a potential source of 6PPD and 6PPD-q from roadways. These practices may be performed by other departments (i.e., road maintenance) or organizations than an environmental or stormwater organization. The criteria developed for this report focuses on the BMPs that are included in stormwater design manuals. A list of the BMPs evaluated and results of the evaluation are included in Appendix 4-1.

High Potential

The source control BMPs identified as having the highest potential were BMPs which could prevent precipitation or runoff from contacting tires, tire particles, other 6PPD and 6PPD-q sources, or prevent these contaminants from entering stormwater infrastructure. Once drained from a road or parking lot the SWMMWW, SWMMEW, and WSDOT HRM list road, roadside ditch, and parking lot source control BMPs, which can involve removal of roadway sediment from roads or parking surfaces, as well as sediment transported to roadside ditches. Examples of these BMPs include street sweeping, cleaning roadside ditches, and cleaning catch basins and storm drainpipes (line cleaning). As mentioned previously in this chapter, 6PPD and 6PPD-q are likely to adhere to soil and organic matter as such, removal of these particles from roadways, parking surfaces, and roadside ditches is therefore anticipated to provide the best reduction. Assumptions in the high treatment potential category include that the BMPs can remove 6PPD and 6PPD-q particle sizes that are likely to be washed off roadways and enter stormwater infrastructure (see Section 4.3.1, Chapter 2).

Medium Potential

Source control BMPs with a medium potential to prevent 6PPD and 6PPD-q from mixing with stormwater runoff included BMPs which provide either partial separation of the contaminants from stormwater or separate a potential minor source of contamination to stormwater, like traffic at a construction site. Source control BMPs which provide a partial separation include education and outreach (E&O) programs. It was assumed for the criteria that a successful E&O program which informed the target audience about the impacts of 6PPD and 6PPD-q (and alternative products in the future) would provide some source control. Construction sites, particularly sites located on or adjacent to highways, were assumed to be a minor source that produce a lower loading of 6PPD and 6PPD-q than a roadway due to the lower number of vehicles at a construction site. As such, construction source control BMPs were assumed to only provide a medium treatment potential.

Low Potential

Source control BMPs with a low potential to prevent 6PPD and 6PPD-q from mixing with stormwater runoff included BMPs which were unlikely to provide a separation between the contaminant source and stormwater, as they are not typically located near a major or minor source of 6PPD or 6PPD-q or appropriate for providing separation of roadway particles. It is unknown if other major sources of 6PPD or 6PPD-q exist aside from the presence in tires or other car parts. As previously noted, this report has been developed focusing primarily on roadway sources.

Source Control BMP Examples

Examples of BMPs with categorized with a high, medium, or low prevention potential to separate stormwater runoff from the contaminants are included in Table 4.5.

Table 4.5 Examples of Source Control BMPs with Different Treatment Potential Categories

Prevention Potential Category	Examples of Source Control BMPs
High	BMPs for Streets and Highways, BMPs for Maintenance of Roadside Ditches
Medium	E&O Programs Related to 6PPD or 6PPD-q, Construction Wheel Wash
Low	BMPs for Temporary Fruit Storage, BMPs for Railroad Yards

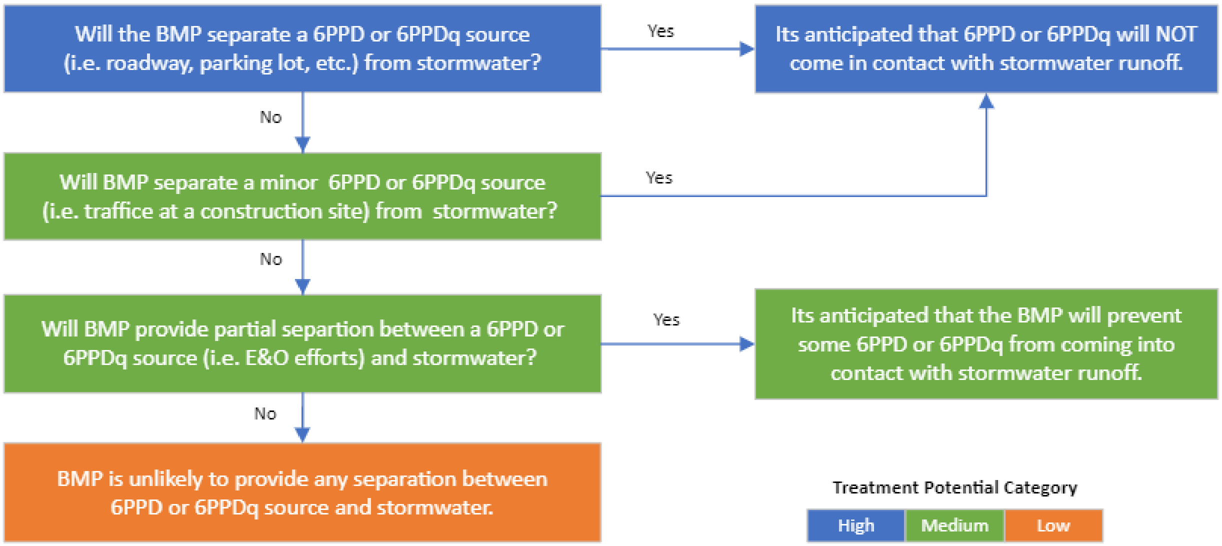

Figure 4.3 Source Control BMP Evaluation Criteria

<u>4.3.3 Results of BMP Evaluation</u>

The BMP evaluation criteria was applied to each flow and treatment BMP and source control BMP in the stormwater design manuals identified in Section 4.2. Table 4.6 summarizes the number of unique BMPs in each treatment and prevent potential category from the SWMMWW, the WSDOT HRM, and BMPs from other states if the BMP was not in the Washington stormwater manuals. All the BMPs identified along with the results from the evaluation are summarized in Appendix 4-1.

Table 4.6 All Unique BMPs (Includes SWMMWW & WSDOT HRM) by Potential Category

Treatment Potential	Flow and Treatment BMPs		Source Control BMPs	
	Number of BMPs for 6PPD	Number of BMPs for 6PPD-q	Number of BMPs for 6PPD	Number of BMPs for 6PPD-q
High	28	28	9	9
Medium	51	51	3	3
Low	14	14	72	72
Total	**93**	**93**	**84**	**84**

4.4 Research Gaps

During the development of the evaluation criteria, gaps in literature were identified, as such assumptions were made to develop the evaluation criteria (Tables 4.2 and 4.3). In addition, general gaps in understanding were identified (not part of the evaluation criteria) which could impact or prevent BMP treatment and the location of BMPs related to the actual loading of 6PPD and 6PPD-q from sources (i.e., roadway and parking lot surfaces). Specifically, loading can inform the life cycle of BMPs, meaning how long the BMP is expected to provide treatment before it needs to be replaced. Additionally, loading can be used to prioritize locations to install BMPs, as locations with higher loading would result in a higher water quality benefit if a BMP were installed downstream of the 6PPD and 6PPD-q source. Further, no relationship between land use, traffic count (ADT), or other indicators was identified in the literature, and no sampling data to characterize the loading from roadways to BMPs or other stormwater infrastructure was found. However, studies did show that other chemicals used in tires are present in higher concentrations in highly urbanized settings (Seiwert B. , Nihemaiti, Troussier, Weyrauch, & Thorsten, 2022; Hu X. , et al., 2022). Additional discussion about prioritizing BMPs locations is included in Section 3.4.

4.4.1 Flow and Treatment BMP Research Gaps

The following gaps were identified during development of the flow and treatment BMP evaluation criteria.

- *Whether and what type of sorption removes contaminants* – contradictory research exists about the efficiency of sorption to remove 6PPD or 6PPD-q (see discussion of High Treatment Potential in Section 4.3.1). More research is needed to understand which media and soil in existing BMPs can remove these contaminants using this treatment process and identify the process responsible for removal.
- *Whether 6PPD and 6PPD-q will remain adhered to soil* – the log K_{ow} and log K_{oc} for 6PPD and 6PPD-q suggest that the contaminants will adhere to soil or organic matter and not be exported to groundwater, however, no field research was found to confirm this. This research gap was also identified in Chapter 2 and is particularly important in knowing if toxicity reduction can be achieved simply by capturing suspended particles of tire wear and bound 6PPD and 6PPD-q.
- *Lethality of the different forms (dissolved, attached to particles, in soil, etc.) and particle sizes containing or adhered to 6PPD and 6PPD-q* – it was unknown what forms or particle sizes BMPs should target to reduce the toxicity of the effluent. Information on the toxicity of the different forms and particle sizes to reduce lethality of stormwater effluent is needed.
- *Residence Time* – The BMP residence time was discussed in the flow and treatment BMP evaluation criteria; specifically, BMPs are not designed to have a residence time equal or greater than the contaminants half-life and are not expected to provide sufficient time for the contaminant in the dissolved phase to decay. However, the majority of the 6PPD and 6PPD-q half-life data was determined from fugacity model results and more research is needed to understand the half-life in stormwater environments and how it will influence BMP treatment.
- *Design guidance to limit re-suspension of sediment in BMPs with permanent pools* – Wet pool BMPs in Ecology's SWMMWW and SWMMEW are designed to limit re-suspension of particles and anoxic conditions. It is unknown whether BMPs were developed similarly for other States' manuals.

4.4.2 Source Control BMP Research Gaps

The following gaps were identified during development of the source control BMP evaluation criteria.

- *Efficacy of source control BMPs* – no research was located on the effectiveness of source control BMPs for preventing 6PPD or 6PPD-q from mixing with stormwater or whether source control BMPs that focus on sediment removal could capture 6PPD and 6PPD-q (based on particle size).
- *Efficacy of E&O programs in reducing 6PPD or 6PPD-q in the environment* – no research on the effectiveness of E&O BMPs in reducing the presence of 6PPD or 6PPD-q in the environment or on roadways was identified.
- *Loading of 6PPD or 6PPD-q from construction site* – no data was identified which described the loading of 6PPD or 6PPD-q from a construction site. It was assumed that the loading of 6PPD or 6PPDq from construction site would be less than a highway, based on the number of vehicles using the site compared to a roadway.

4.5 Recommendations for Next Steps and/or Additional Research

Recommendations for next steps or additional research were identified from the research gaps listed in Section 4.4. The following bullets summarize the recommendations for additional research.

4.5.1 General Recommendations

- *Perform testing of roadway particles to characterize the most common sizes and toxicity of the different forms of 6PPD and 6PPD-q* – understanding the particle size distribution and toxicity of different forms of 6PPD and 6PPDq will help to understand loading from roadways/parking areas and prioritize where BMPs should be located.
- *Perform additional testing to determine if there is an ADT threshold where 6PPD and 6PPD-q concentrations are no longer present in lethal amounts* – understanding where the loading is problematic will allow prioritization to locate BMPs at sites with higher loading.
- *Perform testing to determine loading from construction sites* – an understanding of loading from construction sites (especially highway construction) will help to determine the priority of treating runoff from the sites as well as determine the most effective construction source control and flow and treatment BMPs.

4.5.2 Flow and Treatment BMP Recommendations

- *Perform additional testing to understand the efficacy of sorption* – additional testing is needed to understand whether this treatment process can be used in BMPs to remove 6PPD and 6PPD-q.
- *Perform leach testing of 6PPD and 6PPD-q adhered to soil* – the leach testing will help confirm whether the contaminants will remain adhered to soil and not be exported to groundwater if water flows across the soil and contaminants.
- *Perform field testing to determine what forms (dissolved, adhered to particles, in soil, etc.) and what particle sizes containing or attached to 6PPD and 6PPD-q need to be removed by BMPs to reduce lethality of stormwater effluent* – at the time of this report, no information was available regarding which forms or particle sizes containing or attached to 6PPD and 6PPD-q were toxic, which is needed to determine which forms or particle sizes BMPs should to remove to limit lethality. Additional literature review or lab or field testing may be needed to confirm whether the BMPs can remove these particle sizes.

4.5.3 Source Control BMP Recommendations

- *Perform testing to determine whether solid/TWP removal methods from roadways, parking, and stormwater infrastructure can remove 6PPD and 6PPD-q* – characterizing the solid sizes collected by removal methods may help to understand whether the source control BMPs for roadways, parking, and stormwater infrastructure can reduce 6PPD and 6PPD-q.
- *Conduct a study to assess the potential efficacy of E&O programs* – Conduct an assessment of 6PPD and 6PPD-q sources along with the respective behavior change needed to reduce concentrations of these contaminants and the potential impact of these programs will help determine if an E&O program could provide a measurable reduction of these contaminants. The assessment should also include recommendation for specific E&O campaigns that could be successful. Understanding the potential effectiveness of E&O programs in reducing 6PPD and 6PPD-q in the environment will help to inform the rating for these BMPs.

Appendix 4-1

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Site Design BMPs												
Preserving Natural Vegetation							X			N/A	Low	N/A
Better Site Design							X			N/A	Low	N/A
Impervious Surface Disconnect (D.C., 2020)							X			N/A	Low	N/A
Dispersion BMPs												
Concentrated Flow Dispersion		X							X	High	N/A	Yes
Sheet Flow Dispersion		X							X	High	N/A	Yes
Full Dispersion (natural or engineered)		X							X	High	N/A	Yes
Roof Downspout BMPs												
Downspout Full Infiltration		X							X	High	N/A	Yes
Downspout Dispersion System		X							X	High	N/A	Yes
Perforated Stub-Out Connection							X			Low	N/A	Yes
Infiltration BMPs												
Permeable Pavements		X								Medium	N/A	Yes
Stone storage under permeable pavement or other BMPs (D.C., 2020)									X	High	N/A	Yes
Infiltration Basins/Ponds		X			X				X	High	N/A	Yes
Infiltration Vault (WSDOT, 2019)									X	High		

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Infiltration Trenches		X							X	High	N/A	Yes
Bioretention		X	X		X			X	X	High	N/A	Yes
Bioinfiltration (WSDOT, 2019)		X							x	High	N/A	Yes
Underground Attenuation Facilities										Low	N/A	Yes
Drywells		X								Medium	N/A	Yes
Filtration BMPs												
Basic Sand Filter Basin		X								Medium	N/A	Yes
Large Sand Filter Basin		X								Medium	N/A	Yes
Sand Filter Vault		X								Medium	N/A	Yes
Sand Filter Iron Enhanced (Minnesota, 2021)		X	X							High	N/A	Yes
Linear Sand Filter		X								Medium	N/A	Yes
Media Filter Drain	X	X	X			X			X	High	N/A	Yes
Biofiltration BMPs												
Compost-Amended Vegetated Filter Strips (CAVFS)		X	X						X	High	N/A	Yes
Basic Biofiltration Swale		X						X	X	High	N/A	Yes
Wet Biofiltration Swale		X			X			X	X	High	N/A	Yes

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Continuous Inflow Biofiltration Swale		X								Medium	N/A	Yes
High Gradient Stormwater Step Pool Swale (Minnesota, 2021)	X	X								Medium	N/A	Yes
Vegetated Filter Strip		X								Medium	N/A	Yes
Wetpool BMPs												
Wetponds - Basic and Large	X				X					Medium	N/A	Yes
Wetvaults	X									Medium	N/A	Yes
Stormwater Treatment Wetlands	X	X		X						Medium	N/A	Yes
Submerged Gravel Wetlands (Prince George, 2014)		X	X	X	X					High	N/A	Yes
Combined Detention and Wetpool facilities	X				X					Medium	N/A	Yes
Pretreatment BMPs												
Presettling Basin	X									Medium	N/A	Yes
Pretreatment - Screening and straining devices, including forebays (Minnesota, 2021)	X									Medium	N/A	Yes
Pretreatment - Above ground and below grade storage and settling devices (Minnesota, 2021)	X									Medium	N/A	Yes
Pretreatment - Filtration devices and practices (Minnesota, 2021)	X	X								Medium	N/A	Yes
Misc LID BMPs												
Post-Construction Soil Quality and Depth										Low	N/A	Yes

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Rain Gardens										Low	N/A	Yes
Tree Retention and Tree Planting					X		X			Low	N/A	Yes
Vegetated Roofs							X			Low	N/A	Yes
Reverse Slope Sidewalks							X			Low	N/A	Yes
Minimal Excavation Foundations							X			N/A	Low	N/A
Rainwater Harvesting							X			Low	N/A	Yes
Detention BMPs												
Detention Ponds	X				X					Medium	N/A	Yes
Detention Vaults or Tanks	X									Medium	N/A	Yes
Oil and Water Separator BMPs												
API (Baffle Type) Separator	X									Medium	N/A	Yes
Coalescing Plate (CP) Separator	X									Medium	N/A	Yes
Multi-Chamber Treatment Train (CalTrans, 2019)	X	X								Medium	N/A	Yes
Gross Solids Removal												
Gross Solids Removal Devices (GSRDs): Linear Radial and Inclined Screen (CalTrans, 2019)		X								Medium	N/A	Yes
Traction Sand Traps (CalTrans, 2019)	X	X								Medium	N/A	Yes

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Manufactured Treatment Devices as BMPs[6]												
BayFilter w/ EMC Media	X	X	X							High	N/A	Yes
BaySeparator	X									Medium	N/A	Yes
Aqua-Swirl System	X									Medium	N/A	Yes
BioPod Biofilter	X	X	X	X						High	N/A	Yes
CDS Stormwater Treatment System	X	X								Medium	N/A	Yes
Compost-Amended Biofiltration Swale	X	X	X	X						High	N/A	Yes
Downstream Defender	X									Medium	N/A	Yes
ecoStorm plus	X	X	X			X				High	N/A	Yes
Filterra	X	X	X	X						High	N/A	Yes
FloGard Perk Filter	X	X	X							High	N/A	Yes
Jellyfish	X	X								Medium	N/A	Yes
Media Filtration System							X			Low	N/A	Yes
Modular Wetland System - Linear	X	X		X						Medium	N/A	Yes

[6] Manufactured treatment device treatment mechanisms were determined from information presented in TAPE documents for the device.

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Stormceptor	X						X			Medium	N/A	Yes
StormFilter using PhosphoSorb	X	X	X			X				High	N/A	Yes
StormFilter using ZPG	X	X	X				X			High	N/A	Yes
StormGarden	X	X		X						Medium	N/A	Yes
StormTree	X	X	X	X						High	N/A	Yes
The Kraken	X	X								Medium	N/A	Yes
Up-Flo Filter w/ Filter Ribbons	X	X								Medium	N/A	Yes
Vortechs	X						X			Medium	N/A	Yes
Construction Source Control												
Buffer Zones							X			N/A	Low	N/A
High-Visibility Fence							X			N/A	Low	N/A
Stabilized Construction Access							X			N/A	Medium	Potentially
Wheel Wash							X			N/A	Medium	Potentially
Construction Road / Parking Area Stabilization							X			N/A	Medium	Potentially
Temporary and Permanent Seeding							X			N/A	Low	N/A
Mulching							X			N/A	Low	N/A

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Nets and Blankets							X			N/A	Low	N/A
Plastic Covering							X			N/A	Low	N/A
Sodding							X			N/A	Low	N/A
Topsoiling / Composting							X			N/A	Low	N/A
Polyacrylamide (PAM) for Soil Erosion Protection							X			N/A	Low	N/A
Surface Roughening							X			N/A	Low	N/A
Gradient Terraces							X			N/A	Low	N/A
Dust Control							X			N/A	Low	N/A
Materials on Hand							X			N/A	Low	N/A
Concrete Handling							X			N/A	Low	N/A
Sawcutting and Surfacing							X			N/A	Low	N/A
Material Delivery, Storage, and Containment							X			N/A	Low	N/A
Concrete Washout Area							X			N/A	Low	N/A
Certified Erosion and Sediment Control Lead							X			N/A	Low	N/A
Scheduling							X			N/A	Low	N/A

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Interceptor Dike and Swale		X								Medium	N/A	Yes
Grass-Lined Channels		X								Medium	N/A	Yes
Riprap Channel Lining		X								Medium	N/A	Yes
Water Bars		X								Medium	N/A	Yes
Pipe Slope Drains							X			Low	N/A	Yes
Subsurface Drains							X			Low	N/A	Yes
Level Spreader							X			Low	N/A	Yes
Check Dams		X								Medium	N/A	Yes
Triangular Silt Dike		X								Medium	N/A	Yes
Outlet Protection		X								Medium	N/A	Yes
Inlet Protection		X								Medium	N/A	Yes
Brush Barrier		X								Medium	N/A	Yes
Gravel Filter Berm		X								Medium	N/A	Yes
Silt Fence		X								Medium	N/A	Yes
Vegetated Strip		X								Medium	N/A	Yes

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
Wattles		X								Medium	N/A	Yes
Vegetative Filtration		X							X	High	N/A	Yes
Sediment Trap	X									Medium	N/A	Yes
Sediment Pond (Temporary)	X									Medium	N/A	Yes
Constructed Stormwater Chemical Treatment						X				Low	N/A	Yes
Construction Stormwater Filtration		X								Medium	N/A	Yes
Treating and Disposing of High pH Water						X				Low	N/A	Yes
Source Control Applicable All Sites												
BMPs for Correcting Illicit Discharges to Storm Drains							X			N/A	Low	N/A
BMPs for Formation of a Pollution Prevention Team							X			N/A	Low	N/A
BMPs for Preventative Maintenance/Good Housekeeping							X			N/A	Low	N/A
BMPs for Inspections							X			N/A	Low	N/A
BMPs for Recordkeeping							X			N/A	Low	N/A
BMPs for Spill Prevention and Cleanup							X			N/A	Low	N/A
BMPs for Employee Training							X			N/A	Low	N/A
Source Control Cleaning & Washing												

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
BMPs for Washing and Steam Cleaning Vehicles/Equipment							X			N/A	Low	N/A
BMps for Dock Washing							X			N/A	Low	N/A
BMPs for Portable Water Line Flushing, Water Tank Maintenance, Hydrant Testing							X			N/A	Low	N/A
BMPs for Deicing and Anti-Icing Operations for Airports							X			N/A	High	Yes
Source Control Roads, Ditches, & Parking Lots												
Street Sweeping (Minnesota, 2021)										N/A	Low	N/A
Stormdrain Line Cleaning (Minnesota, 2021)										N/A	Low	N/A
BMPs for Streets and Highways							X			N/A	High	Yes
BMPs for Maintenance of Public and Private Utility Corridors							X			N/A	High	Yes
BMPs for Maintenance of Roadside Ditches							X			N/A	High	Yes
BMPs for Maintenance of Stormwater Drainage and Treatment							X			N/A	High	Yes
BMPs for Parking and Storage of Vehicles and Equipment							X			N/A	High	Yes
BMPs for Urban Streets							X			N/A	High	Yes
Source Control Soil Erosion, Sediment Control, & Landscaping												
BMPs for Dust Control at Disturbed Land Areas and Unpaved Roadways and Parking Lots							X			N/A	High	Yes

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
BMPs for Dust Control at Manufacturing Areas							X			N/A	Low	N/A
BMPs for Lanscaping and Lawn/Vegetation Management							X			N/A	Low	N/A
BMPs for Soil Erosion and Sediment Control at Industrial Sites							X			N/A	Low	N/A
Source Control Storage & Stockpilling												
BMPs for the Storage of Dry Pesticides and Fertilizers							X			N/A	Low	N/A
BMPs for Storage of Liquid, Food Waste, or Dangerous Waste							X			N/A	Low	N/A
BMPs for Storage of Liquids in Permanent Aboveground Tanks							X			N/A	Low	N/A
BMPs for Storage or Transfer (Outside) of Solid Raw Materials							X			N/A	Low	N/A
BMPs for Temporary Fruit Storage							X			N/A	Low	N/A
Source Control Transfer of Liquids & Solid Materials												
BMPs for Fueling at Dedicated Stations							X			N/A	Low	N/A
BMPs for Loading or Unloading Areas for Liquid or Solid Materials							X			N/A	Low	N/A
BMPs for Mobile Fuleing of Vehicles and Heavy Equipment							X			N/A	Low	N/A
BMPs for Spills and Oil and Hazardous Substances							X			N/A	Low	N/A
BMPs for In-Water and Over-Water Fueling							X			N/A	Low	N/A
Source Control Other												

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
BMPs for Nurseries and Greenhouses							X			N/A	Low	N/A
BMPs for Irrigation							X			N/A	Low	N/A
BMPs for Pesticides and an Integrated Pest Management Program							X			N/A	Low	N/A
BMPs for the Building, Repair, and Maintenance of Boats and Ships							X			N/A	Low	N/A
BMPs for Commercial Animal Handling areas							X			N/A	Low	N/A
BMPs for Commercial Composting							X			N/A	Low	N/A
BMPs for Commercial Printing Operations							X			N/A	Low	N/A
BMPs for Log Sorting and Handling							X			N/A	Low	N/A
BMPs for Maintenance and Repair of Vehicles and Equipment							X			N/A	High	Yes
BMPs for Manufacturing Activities - Outside							X			N/A	Low	N/A
BMPs for Painting/Finishing/Coating of Vehicles/Boats/Buildings/Equipment							X			N/A	Low	N/A
BMPs for Railroad Yards							X			N/A	Low	N/A
BMPs for Recyclers and Scrap Yards							X			N/A	Low	N/A
BMPs for Roof/Building Drains at Manufacturing and Commercial Buildings							X			N/A	Low	N/A
BMPs for Wood Treatment Areas							X			N/A	Low	N/A

BMP Name	Density Separation or Sedimentation	Filtration	Sorption	Microbial Activity	Uptake/ Storage	Chemical Treatment	Not Applicable (Source Control/ E&O)	BMP contains Bioretention Media (Compost)	Infiltration	Potential Treatment Rating of Flow and Treatment BMP	Potential Prevention Rating of Source Control BMP	Can the BMP be implemented near sources?
BMPs for Pools, Spas, Hot Tubs, and Fountains							X			N/A	Low	N/A
BMPs for Color Events							X			N/A	Low	N/A
BMPs for Construction Demolition							X			N/A	Low	N/A
BMPs for Pet Waste							X			N/A	Low	N/A
BMPs for Labeling Storm Drain Inlets on your Property							X			N/A	Low	N/A
BMPs for Fertilizer Application							X			N/A	Low	N/A
BMPs for Well, Utility, Directional, and Geotechnical Drilling							X			N/A	Low	N/A
BMPS for Roof Vents							X			N/A	Low	N/A
BMPs for Building, Repair, Remodeling, Painting, and Construction							X			N/A	Low	N/A
BMPs for Goose Waste							X			N/A	Low	N/A

CHAPTER 5: RESEARCH PRIORITIZATION

5.1 Chapter Purpose

The intent of this chapter is to summarize and prioritize the knowledge gaps and next steps identified during the project.

5.2 Overview of Chapter Contents and Work Complete

This chapter contains a prioritized list of the research gaps and next steps that were identified in Chapters 2-4 of this report. Each research gap and associated next step or approach was prioritized into one of three categories: High, Medium, or Low. The categories were developed using best professional judgement guided by input from experts and assuming the highest need is to understand how to capture/contain/treat 6PPD and 6PPD-q generated on roadways and prioritization of where treatment needs to occur first to protect receiving waters. As such, the categories are defined based on the need for the research to understand what BMPs would capture/contain/treat the contaminants and the potential impact on surface waters if current knowledge is inaccurate or incomplete (see Chapter 2 for discussion of modeled parameters).

5.3 Key Findings Summary

Table 5.1 contains a summary of the research needed from each of the chapters. It is important to note that these research needs reflect the current state of knowledge, and that research is ongoing. A topic that is considered low priority at this time may become a high priority as knowledge of 6PPD and 6PPD-q advances. Additionally, research gaps categorized as a low priority are still topics that need to be studied; the low categorization is a ranking, meaning that it is considered low priority only in relation to the remaining research gaps.

The following bullets define the research priority categories.

- **High:** This category includes research that is necessary to determine what treatment processes or BMPs can treat/capture/contain 6PPD or 6PPD-q, and may be limiting the current ability to confidently select or locate BMPs to treat the contaminants The research may help answer multiple questions or informs multiple unknowns regarding 6PPD or 6PPD-q. It also includes research that is necessary to confirm assumptions or hypotheses which, if incorrect, would cause a detrimental environmental impact. For example, testing to confirm that 6PPD and 6PPD-q does not leach from soil, engineered materials, or organic matter under various environmental conditions could confirm several categories of BMPs (infiltration, biofiltration, etc.) could capture/contain/treat the contaminants. If the contaminants do leach in certain conditions, it will be important to know those conditions to limit potential transport and impacts to groundwater and surface waters.
- **Medium:** This category includes research that is not as urgently needed to be able to capture/contain/treat 6PPD and 6PPD-q, but still needs to be answered following the research gaps ranked as high. It also includes research to confirm hypotheses or assumptions regarding the contaminants that would not have as detrimental of an impact to surface waters if the current understanding is inaccurate or incomplete. For example, research gaps related confirming the half-lives of 6PPD and 6PPD-q could potentially impact the ability of filtration BMPs (BMPs with a medium treatment potential) to treat the contaminants, as these BMPs may not contain the contaminants long enough for the contaminants to fully degrade before leaving the BMP. However, the research gap is not expected to impact the ability of infiltration or other BMPs considered to have a high treatment potential, as the contaminants are expected to be captured within the BMP

soil or engineered material and not re-suspended during a storm event. Because this research gap only impacts a category of BMPs or a category of BMPs with a medium or low treatment potential, the research gap is ranked as medium. Research gaps that are necessary to determine prioritization of BMP locations are also included in this category.

- **Low:** This category includes research which informs unknowns regarding the contaminants and prioritization but is not urgently needed to understand how to treat/capture/contain 6PPD or 6PPD-q or only informs one unknown regarding the contaminants. Research gaps that are less necessary to determine prioritization of BMP locations are also included in this category. An example of a low priority research gap includes identification of other sources other than roadways and an understanding of the loading from those sources. As this research gap is not immediately necessary to understand how to capture/contain/treat the contaminants, and addresses prioritization of likely minor sources of 6PPD and 6PPD-q compared to roadways.

Table 5.1 6PPD and 6PPD-q Research Prioritization

Priority/ Urgency	Research Gap	Approach	Chapter
High	Additional testing is needed to confirm leaching of 6PPD and 6PPD-q from soil, engineered materials, and organic matter is not likely, and to understand any conditions where it could occur. This property has a large impact on the fate and transport of the contaminants within the built environment, determines whether existing BMPs would permanently remove the contaminants, and would indicate whether groundwater could be impacted by the contaminants.	Conduct lab or field testing to confirm whether the contaminants remain adhered to soil and organic matter for different environmental conditions.	2, 4
High	Additional testing is needed to confirm the values produced by the Fugacity Model and the half-life of 6PPD-q, as these values impact the persistence of 6PPD and 6PPD-q in the environment and inform the BMP hydraulic residence time needed for certain BMPs (i.e., flow through BMPs). The lab and field testing may also inform the methods of how 6PPD and 6PPD-q are degraded in the built environment.	Conduct lab or field testing to confirm the half-life of both contaminants in different materials and under different environmental conditions.	2, 4
High	Uncertain what land uses, ADT, etc. will trigger the need for treatment BMPs at sites. Also, unknown whether there is an ADT threshold where 6PPD and 6PPD-q concentrations are no longer present in lethal amounts. Understanding where the loading is problematic will allow prioritization of sites with higher concentrations.	Study the location and concentration of TWP to determine what land uses, traffic counts, etc. result in toxic concentrations and subsequently what will trigger the need for treatment BMPs as well as determine if there is a traffic count threshold where 6PPD and 6PPD-q are no longer present in lethal amounts.	3,4
High	Additional testing is needed to understand what forms (dissolved, adhered to particles, in soil, etc.) and what range of particle sizes containing or attached to 6PPD and 6PPD-q need to be removed by BMPs to reduce the lethality of stormwater effluent. It will also be helpful to understand which form the contaminants are typically transported.	Perform field testing to understand what forms of 6PPD and 6PPD-q (dissolved, adhered to particles, in soil, etc.) and sizes of particles containing or attached to 6PPD and 6PPD-q need to be removed by BMPs to reduce the lethality of stormwater effluent.	2, 3, 4
High	Unknown whether BMPs that provide infiltration, dispersion, and biofiltration (including BMPs with bioretention soil media or compost) or sedimentation and filtration BMPs will capture the particle sizes associated with the most readily available concentrations of 6PPD and 6PPD-q.	Perform field testing to determine whether infiltration, sedimentation, and filtration BMPs can remove 6PPD and 6PPD-q particle sizes that will reduce the lethality of the effluent.	4
Medium	No information existing regarding whether solids removal (e.g., street sweeping and line cleaning) BMPs for roadways, parking, and stormwater infrastructure could reduce/capture 6PPD and 6PPD-q in the environment.	Perform field testing to determine whether solids removal methods from roadways parking, and stormwater infrastructure can remove 6PPD and 6PPD-q in the environment.	4
Medium	Unknown how long those particles containing or with 6PPD attached will generate 6PPD-q at different stages of transport.	Conduct lab or field testing to understand for how long particles will generate 6PPD-q under different environmental conditions.	2
Medium	Lack of information on fate and transport of 6PPD-q under environmental conditions other than wet weather events; specifically, how long does it remain bioavailable and toxic in dry conditions, how it is transported outside of wet weather events.	Conduct a study to evaluate concentrations and bioavailability/toxicity of 6PPD-q under environmental conditions other than wet weather events.	3
Medium	It is anticipated that other potential sources, such as athletic fields with artificial turf, junk yards, and auto repair shops and tire stores, will be identified in the future.	Investigate runoff from other potential sources such as athletic fields with artificial turf, junk yards, and auto repair shops and tire stores to determine if BMPs would be beneficial.	3
Medium	Additional testing is needed to understand whether sorption as a treatment process can be used in BMPs to remove 6PPD and 6PPD-q.	Perform additional testing to understand the efficacy of sorption for reducing 6PPD and 6PPD-q and determine which type of sorption (ion exchange or adsorption).	4
Medium	There is a lack of information on loading of 6PPD and 6PPD-q from construction sites. An understanding of loading from construction sites (especially highway construction) will help to determine the priority of treating runoff from the sites as well as determine the most effective construction source control and flow and treatment BMPs.	Perform field testing to determine loading from construction sites (especially highway construction).	4
Low	No information on efficacy of source control BMPs in reducing 6PPD or 6PPD-q in the environment.	Perform field testing of source control BMPs to determine whether they can reduce or prevent 6PPD or 6PPD-q from mixing with stormwater in the environment.	4
Low	No information on efficacy of E&O behavior change programs in reducing 6PPD or 6PPD-q in the environment.	Conduct a study to assess the potential efficacy of E&O behavior change programs.	4
Low	There is a lack of information on 6PPD-q transport dynamics using sites at different distances from roadway sources and at various points during the hydrograph. This information could lead to BMPs that target the part of the storm with the highest concentration.	Study relationship of time or seasons on 6PPD and 6PPD-q concentrations in wet weather events to understand when peak concentrations occur.	3
Low	More information is needed to determine deposition of TWP dust particles through air and deposition of larger particles from tires.	Study the location and concentration of TWP in the environment (e.g., roadway surfaces, gutters, pipe sediments, snow piles, etc.) to determine where highest concentrations occur.	3
Low	Unknown whether other stormwater design manuals develop BMP guidance to limit sediment resuspension when flow enters the BMPs, or anoxic zones in permanent pools.	Perform literature review to determine whether other stormwater manuals develop BMP guidance to limit sediment resuspension when flow enters BMPs, or anoxic zones in BMPs with permanent pools.	4

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